MODERN HOUSING SOLUTIONS FOR HAWAII:
Utilizing Prefabrication Technologies to Develop High Quality Urban Housing in Hawaii

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School of Architecture
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We certify that we have read the D. Arch. Project and that, in our opinion, it is satisfactory in scope and quality as a D. Arch. Project for the degree of Doctorate of Architecture in the School of Architecture, University of Hawai‘i at Manoa.

Doctorate of Architecture Project Committee

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Abstract

The core characteristics of Hawaii have long created a difficult market for the design and construction of modern high-quality homes. Although strategically located in the Pacific and blessed with a lush, resourceful environment, Hawaii is relatively far from other industrial centers and has a limited supply of land. Land and building materials are often cost prohibitive, and the quality of housing suffers accordingly. Large developers have a distinct advantage in this environment and they continue to build low-quality homes that they can sell for premium prices. As a result, the residents of Hawaii consistently get "less" housing for "more" cost relative to other markets in the United States.

This project investigates how modern prefabrication technologies in architecture can be utilized to create high-quality, high-performance homes at lower costs in Honolulu, Hawaii's urban center. Whereas previous prefabrication efforts have required mass production or standardization to be economically viable, advances in digital design and fabrication are now allowing architects to design and build cheaper and in non-conventional ways. These emerging technologies will help architects introduce creative but cost-effective housing solutions appropriate to Hawaii in a market dominated by generic and limited developer-driven housing.

A townhouse prototype design for Honolulu will be proposed that utilizes structural concrete insulated wall and floor panels as a modern prefabricated building element. This design will illustrate the benefits and opportunities offered by prefabrication tools and technologies such as panelized building systems, building information modeling, computer numerical controlled fabrication, and digital parametric design variation.

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1. Introduction

> "Everybody, quite rightly, dreams of sheltering himself in a sure and permanent home of his own. This dream, because it is impossible in the existing state of things, is deemed incapable of realization and so provokes an actual state of sentimental hysteria; to build one's own house is very much like making one's will…"
>
> - Le Corbusier, *Towards a New Architecture*, 1923[1]

1.1. The Dream of Home Ownership

This project emerges out of the everyday American dream of one day owning a home. While this ambition is simple in concept, rising land and construction costs have made it more and more difficult to achieve, particularly in and around desirable population centers like the Island of Oahu in Hawaii. Despite these challenges, people are able to find paths to home ownership through a mixture of perseverance, creativity, and luck. However, for these people, the design quality of housing received is rarely justified by the amount of money they spent. Thus the question is posed: Given the difficulty of purchasing a home today in a market like Oahu, what can architects and the building industry do to provide consumers with the highest quality housing product at the lowest price? How can potential homeowners get more for less?

1.2. Technology the Enabler

The answer to this question of how to create more for less is to turn to the innovations and solutions that modern technology can offer. Throughout history, technology has been an enabler that has helped industries evolve, allowing them to grow increasingly efficient, specialized, and innovative. In turn, consumers benefit as the products and services provided by these industries become more accessible and affordable. The

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[1] Le Corbusier, *Towards a New Architecture* (New York: Praeger Publishers, 1960), 245.

overall value of these products and services jumps dramatically, as more features and options are offered while at the same time it becomes cheaper to provide them. While technology has been key to the rapid evolution of industrial design and manufacturing, unfortunately it has not yet been similarly utilized in the building industry.

In many regards, technology has advanced the practice of architecture tremendously. With a wide array of software and hardware tools at their disposal, architects today can draft with more speed and precision, model and render more realistically, employ new methods of visualization and prototyping, and manage business processes more efficiently. Specialization within the field has increased with the technological advancement of architecture, as more and more consultants are now required to complete complex projects. While this specialization has helped architecture branch out into new fields, it has also resulted in the decreased involvement of architects in the actual fabrication and construction of buildings. This is a significant contrast from the early days of architecture, when the architect also served as the master builder, overseeing everything from design through construction.

As a result of this separation in responsibilities, the current level of integration between design and construction is somewhat clumsy and inefficient. What the architect designs may not be what the contractor eventually builds, primarily because the architect may lack a full understanding of how the building components are fabricated and pieced together and the contractor may lack a full understanding of the designer's true intent. Furthermore, designers are often limited to what the contractors can realistically and inexpensively fabricate, which in turn limits the complexity of forms and spaces that can be designed. While technology has allowed each party to do their part of the work faster and more efficiently, a gap still remains between the actual design and construction processes of a building. As long as this separation in responsibilities remains and the industry continues to specialize, it will be difficult to introduce innovate solutions that can reduce the cost of construction and lower the price of housing for the end consumer.

1.3. The Potential of Prefabrication Technology

Fortunately, recent movements in prefabrication technology are opening up new opportunities that allow architects to reexamine their role in the fabrication of the buildings they design. For example, digital design and manufacturing processes are bridging the gap between design and fabrication by allowing architects to directly design three-dimensional construction components on computers and then send it to a computer numerically controlled (CNC) milling machine for instant fabrication. In these instances, the architect is now required to more carefully design how the component is to be built rather than to just let the contractor figure it out. Not only does this return more detailed design control to the architect, but it also allows for the exploration of complex forms at a lower cost of fabrication. For the end consumer, a more innovative housing product is now available at a lesser cost.

Older concepts in prefabrication such as factory-built modular housing are also re-emerging in the collective movement of architecture, which is also opening up ways for architects to take on bigger roles in the fabrication of their designs. Although the integration of housing construction and industrial processes has been an age-old pursuit taken on by important modern architects such as Le Corbusier and Walter Gropius, few have succeeded in creating a lasting model. Instead, the manufactured home industry, devoid of both architects and innovative design, has been the most successful in marrying building construction with industrial factory processes. In the year 2000, manufactured homes accounted for 30 percent of all new single-family houses sold in the United States[2].

Despite these past struggles, architects are starting to again find opportunities to explore factory-built housing. These opportunities are being driven by a mix of factors that include the rising cost of construction, increasing environmental concerns, and the technological refinement of industrial fabrication processes in related design fields. Several architects are actively shifting the general perception of modular housing from low-quality to high-quality. Prefab homes are touted as stylish high performance units that require little on-site construction time and employ environmentally responsible construction methods. In addition to being more energy efficient and structurally sound than a comparable stick-built home, they are estimated to cost less if well planned and developed. The renewed involvement of architects in this industry is promising because the infusion of design into a traditionally unimaginative industry may provide consumers with higher quality housing at factory-built savings.

1.4. Getting More for Less in Oahu

When these advancements of prefabrication technology are considered in the context of Oahu, it becomes clear that the cost savings from prefab construction is minor relative to the overall cost of land. Unless someone already owns land, the cost of building a single-family home in Oahu is prohibitive whether built conventionally or otherwise. This factor alone reduces the potential impact of prefabrication technology on the current

[2] Colin Davies, *The Prefabricated Home* (London: Reaktion Books, 2005), 87.

housing industry in Oahu. Therefore it makes sense to look beyond the conventional ideal of a single-family home, and to apply prefabrication technology and methods to the development of alternative multi-family housing units in dense urban areas like Honolulu. The ever-growing population and future mass-transit proposals reinforce the idea that these types of alternative housing solutions must be considered. In Oahu's near future, urban housing may be the best option for people to realize their dreams of buying a high quality home at an affordable price.

As architects gain more familiarity with modern methods of prefabrication and begin to implement these strategies in their designs, they will begin to wield more power and responsibility in the construction of their buildings. This greater knowledge of how their building is pieced together will push innovative design and simplify fabrication and assembly processes. Through research and design exploration of these methods and processes, this project will show how prefabrication technology can be applied to future housing design in Hawaii to significantly increase the standard of value and help push design to another level. Through creative design and modern technology in architecture and construction, everyone, even those living in urban centers like Oahu, should be able to get the most value for their money and purchase high quality housing for reasonable and competitive prices.

2. Improving the Quality and Value of Housing on Oahu

Before the potential of prefabrication technology can be explored as viable option to produce high-quality high-value housing in Oahu, it is important to take a closer look at the characteristics of the region and the current housing trends. This will help to identify existing challenges and possible opportunities that can better inform how the processes of design and construction can be improved to reach the end goal. An overview and analysis of Oahu's housing market will be provided followed by broad proposals for future improvements.

2.1. Background on Oahu

Separated from the mainland United States by 2,300 miles of ocean, Hawaii is a state unlike any other. The only island state, it enjoys a relatively constant tropical climate throughout the year with humidity tempered by constant trade winds. Ethnically, Hawaii has the largest percentage of Asian Americans and is only one of four states where non-Hispanic whites do not form a majority[3]. Oahu is by far the most populous island in Hawaii, accounting for approximately 75% of the state's population. According to the United States Census Bureau in 2006, an estimated 1,285,498 people live in the state of Hawaii, with 909,863 of those people living on the island of Oahu[4]. The population of Oahu is further centered in the urban capitol city of Honolulu, where an estimated 380,149 reside[5]. Oahu has a landmass of 596.7 square miles, giving it a population density of roughly 1,500 people per square mile.

[3] "Hawaii," *Wikipedia*, http://en.wikipedia.org/wiki/Hawaii (accessed November 16, 2007).
[4] U.S. Census Bureau, "Hawaii County QuickFacts," *U.S. Census Bureau*, http://quickfacts.census.gov/qfd/states/15/15003.html (accessed November 16, 2007).
[5] Ibid.

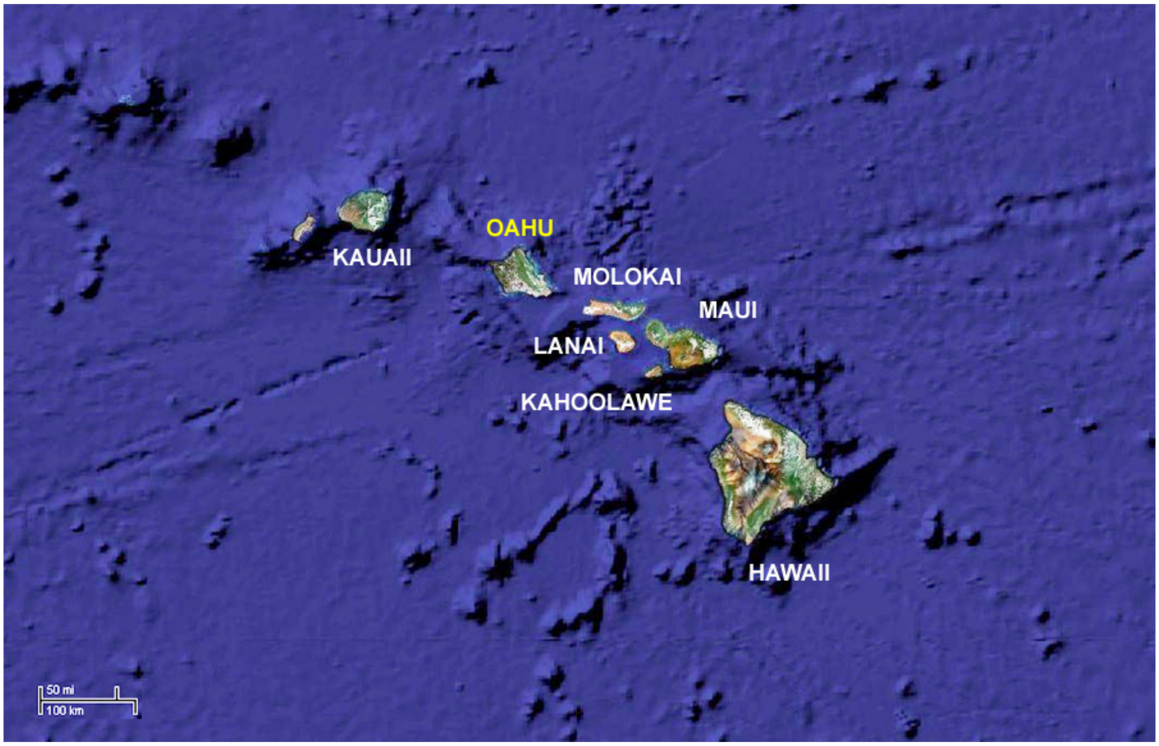

Figure 2.1. Satellite Imagery of the Hawaiian Islands

2.2. Oahu's Housing Market

According to *Forbes Magazine*, in 2007 Honolulu was ranked the 6th most overpriced real estate market, following San Diego, Miami, Sacramento, San Francisco, and Washington DC[6]. This ranking factors in a methodology developed by *Forbes* called a "price-to-earnings ratio" that is somewhat analogous to the P/E of a stock in the financial market. By taking each market's median house price divided by annual rents minus taxes and insurance for the properties, they attempted to measure the price a homeowner would pay for one dollar of return. Essentially, the higher the P/E ratio for the real estate market, the more overpriced it was, as homeowners would have to pay more to get the same return value of housing as in other markets. In addition to using

[6] Matt Woolsey, "America's Most Overpriced Real-Estate Markets," *Forbes Magazine*, http://www.forbes.com/2007/05/03/market-housing-overpriced-forbeslife-cx_mw_0504overpriced.html (accessed November 17, 2007).

this metric to rank the cities, Forbes factored in housing price trends and an “affordability index” that factors in income rates and cost of living by determining what percentage of the market’s population can afford a median priced home, assuming a 6% mortgage rate. Subjective quality of life factors such as weather were not considered.

Honolulu has a median home price of $630,000 and scored the 3rd highest P/E along with the 11th lowest affordability index and an even housing price trend. In comparison, San Diego had a median home price of $601,800, scored the 5th highest P/E along with the 2nd lowest affordability index and a declining -4.5% housing price trend. The low affordability and relatively large declining price trend in San Diego is indicative of its number one ranking on *Forbes’* most overprice real estate markets list. Analyzing Honolulu’s numbers, we see that the affordability of housing is better than ten other large metropolitan areas in the US, but the high P/E highlights that the Honolulu home buyer’s dollar does not get them as much in return. One of the primary goals of this project is to look at alternative ways to reduce this ratio; not necessarily by reducing the market’s median house price, but instead by increasing the quality of the product, allowing the house to have a much higher value at the same price.

2.3. Affordability of Oahu Homes

In Oahu, there are currently 329,300 housing units, with a 54.6% homeownership rate[7]. The median sales price in 2006 was $630,000 for a single-family home and $310,000 for condominiums[8]. The median household income is $54,714. According to the *U.S. Department of Housing and Urban Development*, “the generally accepted definition of

[7] U.S. Census Bureau, “Honolulu County QuickFacts,” 2007.
[8] Honolulu Board of Realtors, “Annual Residential Resales Data for Oahu,” *Hawaii Real Estate Central*, http://www.hicentral.com/pdfs/annsales.pdf (accessed November 17, 2007).

affordability is for a household to pay no more than 30 percent of its annual income on housing[9]." To meet the above definition, the median income household in Hawaii can only afford to pay $16,414 a year or $1,368 a month, which means they will only be able to afford a traditional 30-year fixed-rate 6% mortgage of $230,000. Without a significant down payment, this is clearly not enough income to afford the average condominium in Oahu, never mind a single-family home.

Table 2.1. Number and Median Sales Price of Single Family Home and Condominium Units Sold in Oahu from 1996 to 2006

	Single Family Homes				Condominiums			
Year	Units Sold	% Change	Median Sales Price	% Change	Units Sold	% Change	Median Sales Price	% Change
1996	1,749	6.5%	$335,000	-4.0%	1,990	-11.9%	$175,000	-3.8%
1997	2,025	15.8%	$307,000	-8.4%	2,100	5.5%	$150,000	-14.3%
1998	2,495	23.2%	$297,000	-3.3%	2,632	25.3%	$135,000	-10.0%
1999	2,853	14.3%	$290,000	-2.4%	3,298	25.3%	$125,000	-7.4%
2000	3,181	11.5%	$295,000	1.7%	3,926	19.0%	$125,000	0.0%
2001	3,406	7.1%	$299,900	1.7%	4,261	8.5%	$133,000	6.4%
2002	3,906	14.7%	$335,000	11.7%	5,406	26.9%	$152,000	14.3%
2003	4,419	13.1%	$380,000	13.4%	6,907	27.8%	$175,000	15.1%
2004	4,702	6.4%	$460,000	21.1%	7,888	14.2%	$208,000	19.1%
2005	4,617	-1.8%	$590,000	28.3%	7,990	1.3%	$269,000	29.0%
2006	4,041	-12.5%	$630,000	6.8%	6,380	-20.2%	$310,000	15.2%

In 2006, there was a decline in homes, apartment, and condominium units sold in Oahu, perhaps indicating that the real estate market was slowing down and people were no longer as able or willing to pay the cost of home ownership. Median sales price began to level off, only increasing 6.8% for single-family homes and 15.2% for apartments and condominiums. In contrast, from 2004 to 2005 alone, median sales price of homes had increased an astonishing 50%. While many markets in the United States have seen both sales and prices dive in 2007, Oahu sales prices are in a more stable position.

[9] U.S. Department of Housing and Urban Development, "Affordable Housing," *Community Planning and Development – HUD*, http://www.hud.gov/offices/cpd/affordablehousing/index.cfm (accessed November 17, 2007).

Local economists believe that over the next few years, prices will continue to flatten rather than drop like in the mainland due to a strong growing economy, low unemployment rate, and rising personal income[10]. Others further believe that the increase in sales price was skewed by the sales of higher-end luxury homes and that overall sale prices are declining[11]. Regardless of whether median prices will stabilize or decline, what is clear is that fewer homes are being sold and consumers who can afford to purchase homes will be demanding more for their money rather than overpaying for a home.

Figure 2.2. Examples of Low-Quality Multi-Family housing (left) and Generic Developer-Driven Single-Family Housing (right) in Oahu

So what can this all mean for the development of housing and Oahu's real estate market in the near future? The issue of affordability is a complex one that is beyond the scope of this project. However, a quick glance at the data immediately reveals that single-

[10] Andrew Gomes, "Honolulu Home Resale Prices Remain Stable," *The Honolulu Advertiser*, November 2, 2007, http://the.honoluluadvertiser.com/article/2007/Nov/02/bz/hawaii711020332.html (accessed November 17, 2007).
[11] Ibid.

family homes are not by federal standards affordable to the majority of Oahu residents. Even condominiums are not currently affordable by these standards. With an economy that continues to grow and a decline in home values and resale prices, the affordability gap can be slightly decreased. Realistically though, it is highly unlikely that personal incomes grow and sales prices drop in Oahu to the point that a median income family can purchase a home using only 30% of their income a year. The primary reason for this is that there is very little land available in Oahu for private development. Therefore, prices are driven up since there may not be enough supply to meet the demand. The limited availability of land then becomes one of the major obstacles of making housing affordable on Oahu.

2.4. Architects and the Homebuilding Industry

Given that the pricing and affordability of homes is primarily dictated by forces outside of architecture such as land availability, local incomes, and lending interest rates, it makes more sense to look at what architects and homebuilders can do to increase the quality of homes at current price levels. This is important for a variety of reasons. A high quality house will require less maintenance and future renovation, use less energy, appreciate in value faster, demand higher rents, and provide a better environment for the tenants' physical and psychological health. In the long run, the improvement of the quality of housing is a more sustainable approach toward pricing stability in the real estate market.

Homebuilders and architects can directly improve the quality of their product through design, fabrication, assembly, and construction decisions. If they can do this without also increasing the cost for them to design and build the house, they will be able to increase the value of their product. While this sounds obvious, it is simply not happening in the homebuilding industry. One major problem is that architects, who are trained to provide this level of design, are often not involved in most residential development. In the current model of homebuilding economics, architects cannot compete with large housing developers who are able to purchase large tracts of land and speculatively develop one-size-fits-all homes. Instead most of the residential works that architects are commissioned to design are custom homes for specific clients, which account for a tiny percentage of homes built in the United States.

Generally, homebuilders are able to competitively price their homes by building in mass and by using standardized designs, components, and construction methods. On a house-by-house basis, they can adjust the final cost of the home through the variation of finish materials. The involvement of architects in the homebuilding industry is limited and thus designs have remained fairly standard for decades without any significant progression. Most improvements have been in the quality and performance of the materials and appliances with little being done to the quality of the design and the home living experience. If the large majority of homes continue to be developed in this manner, it is unlikely that there will be any significant increase in the quality and value of homes being sold.

2.5. Limited Progress in the Homebuilding Industry

While the lack of architects' involvement is part of the reason why there has been little innovation and progression in housing, other factors also contribute. In most modern industries, the improvement of quality and reduction of prices is already happening on a regular basis. Automobiles, personal technology devices, and computers are all simple examples of this, where older products are constantly either replaced with new and improved products or their prices are lowered. Unfortunately, the homebuilding industry has not been able to follow suit. Kent Larson, director of MIT's House_n project explains:

> "Most major companies outside of housing compete internationally, with innovation on one side of the globe instantly rippling across to the other. New materials, technologies, and processes are adopted in just months. Industrial behemoths have become lean, agile, integrated, and digital - they tap information in real time… In housing, competition is primarily local, processes are labor intensive, and innovations take an average seventeen years to find their way into homes. More sophisticated technology is found a $39.00 Furby doll than in many new houses.
>
> We assume that this year's cell phone or disk player is dramatically more useful, higher quality, and less expensive than last year's. Customers are demanding more for less from their products - and getting it… Except for the vanishing small percentage of homes designed by architects for individual adventurous clients, the U.S. housing industry produces variations of the same low-grade, standard product that it has been making for the past 50 years. There is a perception that housing gives you less for more with each passing year[12]."

Being that buying a home is often both a financial and emotional investment, it is important for a homebuyer to purchase a high-quality high-performance functional home that suits their needs and they enjoy living in. The quality of the living environment is just as important as concept of home ownership itself. Naturally, they want to get the best possible house for the amount of money they are able to spend. On the other side of the equation, homebuilders understandably want to get the most money for what they can competitively get by with. Because the competition is primarily local, homebuyers don't benefit from the global forces of free market competition that usually provides higher quality and more variety at lower prices.

[12] Kent Larson, "The Home of the Future," *A+U* 361 (October 2000): 63.

All this has the potential to change as the evolving world brings about new opportunities for change. For one, the Baby Boomer generation is now one of the largest buyers of new homes, and their purchasing values are different from their depression-era parents. They are demanding more choice, sophistication, and flexibility in housing[13]. Because technology has leveled the playing field by allowing everyone easy access to information through the Internet, the modern homebuyer is much more savvy and informed. There is a greater awareness of the benefits of good design and also what they are able to get for their dollar. The one-size-fits-all designs of speculative housing can no longer adequately fulfill the needs of a modern lifestyle. Homebuilders who want to compete in this new era will be required to collaborate with architects and the design profession can help them to adopt design practices that result in more functional, flexible, innovative, and well-built homes. As proven in other industries, spending more on design can give a significant competitive edge in the long run, overcoming higher sales prices initially and smaller profits margins. People are now willing to spend more for a well-designed product that they feel comfortable using and that offers unique or customizable features.

With an improved market demanding more for less in housing, architects and homebuilders can look to modern technologies and manufacturing processes to push design and innovation without adding any extra cost. In particular, emerging prefabrication technologies, described in later chapters, will provide an opportunity for architects to design higher quality homes that incorporate architectural features and components at a negligible increase in cost. As designers of the built environment, architects can guide this transition to a more integrated design and construction environment reflective of modern technologies and capabilities.

[13] Ibid.

2.6. Alternatives for Future Housing in Oahu

In conjunction with exploring ways to improve the quality of housing in Oahu, it is also important to investigate alternative modes of housing development that may become viable in Oahu's future. The high cost of single-family homes and the limitations of typical condominiums and apartments leave plenty to be desired and drive the need for new modes of living in the future.

Given the population density of Oahu, it makes sense that 45% of the units that residents currently live in are in multi-unit structures[14]. These multi-family buildings can range from duplexes to high-rise condominiums and apartment buildings depending on the zoning and the neighborhoods they are located in. Despite the density, Oahu is still a very car-centric island, with 734,270 registered vehicles in 2006[15]. That is nearly a car a person, which is alarming given the size of the island. It also contributes to a growing traffic problem. The only areas in Oahu that offer a more urban, mixed-use, and pedestrian friendly environment are the downtown Honolulu business district and the tourism based Waikiki area. Most other neighborhoods require vehicular transportation to run everyday errands.

The United States Census Bureau projects that the state of Hawaii will have a population of 1,466,046 people by the year 2030[16]. With this expected growth, it seems even less likely that people will be able to afford single-family homes in the future. Furthermore, with more cars on the road, gridlock will only get worse. These pending problems

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[14] U.S. Census Bureau, "Hawaii County QuickFacts," 2007.
[15] Dan Nakaso, "Hawaii Vehicles Nearly Match State Population," *The Honolulu Advertiser*, June 25, 2007, http://the.honoluluadvertiser.com/article/2007/Jun/25/ln/FP706250359.html (accessed November 18, 2007).
[16] U.S. Census Bureau, "Interim Projections of the Total Population for the United States and States: April 1, 2000 to July 1, 2030," *U.S. Census Bureau*, http://www.census.gov/population/projections/SummaryTabA1.pdf (accessed November 18, 2007).

indicate that housing developers need to begin to seek alternative and sustainable modes of housing for the future that combine better-planned density and encourage more walking and use of public transportation. To support the growing population and to create more sustainable communities, there needs to be a wider variety of housing and living options available in Oahu, from single-family homes for larger families to lofts and studios for young professionals.

On January 7, 2006, Honolulu Mayor Mufi Hannemann signed a bill to officially commit to develop a fixed guideway mass-transit system, after almost 40 years of debate and failed initiatives[17]. The project is projected to be the largest and most expensive public works project in the history of Hawaii, with an estimated price-tag of $5 billion. Called the Honolulu High-Capacity Transit Corridor Project, the fixed guideway will connect the 30-mile stretch between Kapolei and the University of Hawaii at Manoa, with potential offshoots to the airport and Waikiki areas. As the state begins to prepare for the preliminary design and engineering of the system, they are trying to finalize decisions on the type of transit system, the route through existing cities and neighborhoods, and stop locations.

[17] Will Hoover, "Mass Transit Plan Signed and Sealed," *The Honolulu Advertiser*, January 7, 2007, http://the.honoluluadvertiser.com/article/2007/Jan/07/ln/FP701070378.html (accessed November 23, 2007).

Figure 2.3. Map of Proposed Honolulu High-Capacity Transit Corridor Project

From a development standpoint, the proposed mass-transit system is a golden opportunity to revitalize neighborhoods and communities around the proposed route. The Honolulu City Council has recognized the importance of Transit Oriented Development (TOD) and they are requiring that a new zoning ordinance is established before construction starts on the railway stations[18]. The zoning will follow principles of smart, sustainable, and healthy growth and planning by providing a mixture of uses that provide denser, pedestrian and public transit oriented areas for living, working, and playing. More specifically, TOD will look at an area within about one quarter mile around a transit station and establish minimum densities for commercial and residential zones, minimize the amount of off-street surface parking around commercial buildings by moving parking underground and into structures, and plan a variety of housing densities,

[18] "Honolulu On The Move Newsletter," Honolulu High-Capacity Transit Corridor Project, November 2007, http://www.honolulutransit.org/more_info/library/files/November%20Newsletter.pdf (accessed November 23, 2007).

types, prices, and ownership patterns that are all within walking distance to the transit nodes[19]. Benefits of TOD planning can be seen in land conservation, better air quality, increases in affordable housing, higher profits for businesses, and a more cohesive community.

Figure 2.4. Renderings of Proposed Elevated Fixed-Guideway Rail Transit Structure in Various Oahu Neighborhoods

With increased density and the mixing of residential and commercial spaces, there is an opportunity to provide a wide mix of housing types and pricing that will include condominiums, apartments, and townhomes in TOD. In their TOD assessment, the American Planning Association Hawaii Chapter states, “The City’s proposed transit

[19] American Planning Association Hawaii Chapter, “Transit and Transit Oriented Development,” APA Hawaii, August 2007, http://www.hawaiiapa.org/pdf/transit_and_tod_paper_rev.pdf (accessed November 24, 2007): 12.

project provides an important planning tool to focus on and encourage mixed use development including a full range of housing choices. Since transit ridership is also dependant on resident demand, housing and transit have an important mutual relationship[20]." Integrated with the transit station and the commercial component of the neighborhood, exciting live-work environments can be generated.

A future model of transit-centered neighborhoods offers architects the chance to redesign what modern living in Oahu can become. There is a wide range of housing design opportunities within these transit nodes, from affordable housing units to luxury condominium units. And while there are plenty of urban cities that serve as excellent precedents for mixed-use dense housing development, Hawaii offers many elements and traits that will potentially inspire unique models of urban living. Combined with the utilization of new methodologies of design, fabrication and construction, the creation of new typologies of Hawaiian urban living will allow architects and designers to once again play a larger role in housing, the most personal architecture of all.

[20] American Planning Association Hawaii Chapter, 2007.

3. Past, Present, and Future Directions of Prefabrication

> "In the developed world the great majority of buildings, perhaps 80 per cent by value, are not designed by architects and fall outside the architecture field. Yet inside the architecture field, in schools of architecture for example, it is normal to speak and act as if all buildings were designed by architects. It is a fiction tacitly maintained to preserve the illusion that architecture is a real force for change in the world. Ironically, this self-delusion is one of the reasons why architecture is at present not a real force for change in the world. Most of the non-architectural 80 per cent of buildings are houses. Very few ordinary houses count as architecture. This is another of architecture's guilty secrets: that it fails to have any effect on most people's most intimate experience of buildings. Combine this with the widening gulf between architecture and construction and you can begin to see why the prefabricated house is architecture's biggest challenge."
>
> - Colin Davies, *The Prefabricated Home*, 2005[21]

> "It's the holy grail of modern architecture."
>
> - Stephen Kieran on affordable, prefab, mass produced housing[22]

3.1. The Concept of Prefabrication

Prefabrication is by no means a new concept in the construction industry. It is simply the byproduct of industrial evolution and specialization, as manufacturers pursue faster, better, and cheaper methods of production. For example, in the history of wood construction, builders have progressed from cutting and processing logs on site, to using dimensional lumber cut off-site, and to now utilizing prefabricated wood framed wall panels or entire modules. Each step in this progression utilizes methods that allow more of the construction to be completed off site. All advancements are driven by economics, as builders take advantage of new technologies to reduce the amount of expensive on-site labor needed. Architects Peter and Mark Anderson summarize this idea, stating that "the primary purpose of prefabrication is to produce building components in an efficient

[21] Davies, 8.
[22] Inga Saffron, "Custom Prefab Home Is at One With Nature and Technology," *The Washington Post*, July 14, 2007, http://www.washingtonpost.com/wp-dyn/content/article/2007/07/13/AR2007071300787_pf.html (accessed November 30, 2007).

work environment with access to specialized skills and equipment in order to reduce cost and time expenditures on the site while enhancing quality and consistency[23]."

For the traditional stick-built home construction industry, this progress in prefabrication essentially ended with the invention of the balloon frame structure in the mid 1800s[24]. Although these structurally efficient stud wall based structures have become the staple of residential construction, they are still very much constructed like they were two centuries ago, by shipping the dimensioned lumber to the site and nailing the components together. For a variety of reasons, prefabrication of these wall components or entire framed room modules in order to speed up construction has not yet become the preferred way to build.

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[23] Mark Anderson and Peter Anderson, *Prefab Prototypes: Site-specific Design for Offsite Construction* (New York: Princeton Architectural Press, 2006), 7.
[24] Davies, 44.

Figure 3.1. Conventional Wood Framed Stick-Built Home Construction

3.2. Defining Prefabrication

As mentioned previously, prefabrication takes place on several scales and is broadly defined. Thus, before proceeding, it will prove useful to define some terms commonly used when talking about factory prefabrication in the building industry. While the term “Homes” will be used for these definitions, the concepts can be applied to other types of buildings. The following are four prefabricated construction concepts common today.

- Manufactured / Mobile Homes – Manufactured homes are built entirely in a factory with a permanent internal structural support system (a steel chassis) that allows them to be supported by wheels for transportation. They commonly are composed of one building module twelve to fourteen feet wide by seventy or more feet long (single-wide) or two building modules that allow the width to increase to twenty-four feet or more (double-wide). More recently, two-story models have been introduced. The maximum dimensions are determined by state transportation laws. Manufactured homes may be placed on manufactured home parks or on owned or rented property. The construction and installation of manufactured homes is not subject to local building codes and is instead regulated by the U.S. Department of Housing and Urban Development (HUD), through the Federal Manufactured Home Construction and Safety Standards (HUD Code), which went into effect on June 15, 1976[25]. Manufactured homes produced prior to this date are called mobile homes. HUD code regulates design and construction, strength and durability, transportability, fire resistance, energy efficiency, quality, and mechanical and electrical systems. A study in 1997 by an independent counsel determined that the HUD code is comparable to general local building codes[26].

[25] Manufactured Housing Institute, "Understanding Today's Manufactured Housing," *Manufactured Housing Institute* http://www.manufacturedhousing.org/understanding_today2006/mhi_understanding_today.pdf (accessed November 27, 2007), 2.
[26] Ibid.

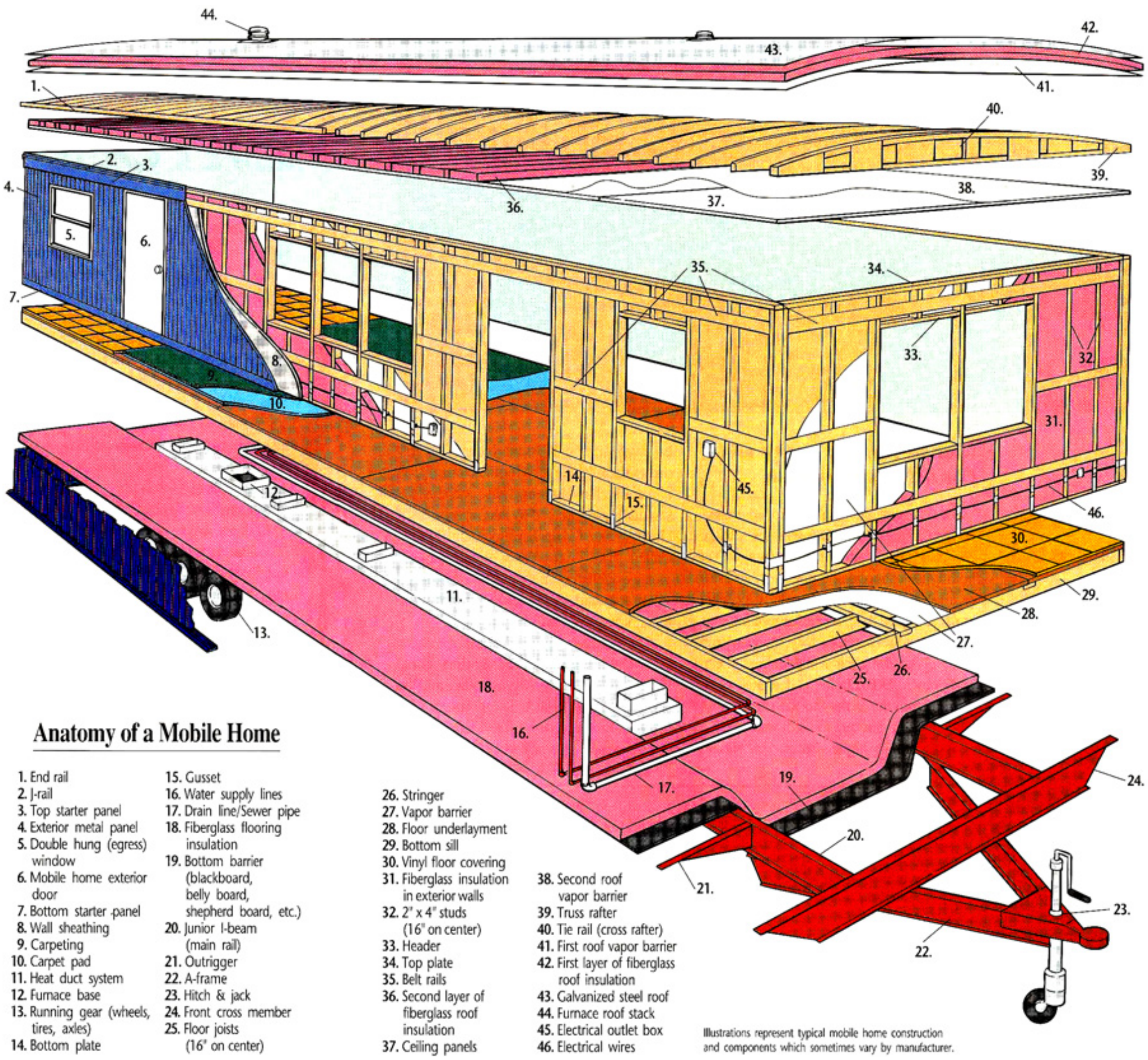

Figure 3.2. Diagram of the Components of a Manufactured / Mobile Home

- Modular Homes – Unlike manufactured homes, modular homes do not have to be built on a permanent steel chassis for transportation. However they are still entirely factory constructed and need enough internal strength and stability to be transported to their permanent site and lifted or craned into position. Modular homes are composed of one or more modules, each whose size is limited by state transportation laws. Once on site, modules may be stacked, placed side by side, or arranged in any other format specified by the design. Modular homes offer much more design flexibility than Manufactured homes. Because they are intended to sit on a permanent foundation, they are built to local, state, or regional building codes instead of the HUD code and are subject to property taxes.

Figure 3.3. Modern Prefabricated Modular Home by Marmol Radziner Prefab

- Panelized / Componentized Homes – Flat component assemblies such as completed wall panels, roof trusses, partitions, and floor assemblies are built in the factory and then shipped out to the site where they are assembled. Components like wall panels will often be nearly finished with windows, doors, wiring, and exterior siding. Sometimes prefabricated homes will employ a combination of modular and componentized parts. Like modular homes, panelized homes are built to be site permanent and are therefore built to local, state, or regional building codes. Panelized homes are generally easier and cheaper to ship as they can be compactly bundled and moved on fewer and smaller vehicles.

Figure 3.4. Panelized Home Built from Structural Insulated Panels

- Pre-Cut Homes – All the materials to build the house are pre-cut and then shipped out to the site where they are assembled. These pre-cut materials are the basic elements of the house and are not yet assembled into more detailed components and assemblies like in the panelized house. Examples of pre-cut homes include catalog kit homes, log homes, and dome homes. These homes are built to local, state, or regional building codes.

Figure 3.5. Pre-cut Kit Homes from Lindal Cedar Homes

The next logical question to ask is what are the major advantages of utilizing these methods of prefabrication? The generally accepted answers to this question are below:

- Time is Saved – Because components or modules are constructed in the factory under controlled supervised scheduling and efficient assembly lines, they are fabricated more quickly. Construction trades and building inspectors are able to work under one roof and are scheduled so that there is minimal downtime or delay. Inclement weather is no longer a potential delay factor. Once the prefabricated components or modules are shipped to the site, it does not take much time to assemble them, allowing the client to move in much faster.

- Money is Saved – Materials can be purchased in bulk at lower negotiated prices since multiple units will usually be built. Also the factory is set up for maximum efficiency and minimum waste. Less skilled labor is needed as employees can be trained only to complete specific tasks. This is an important advantage because of the shrinking traditional construction labor pool, which can cause delays or increase construction costs. An example of the costs savings can be seen when comparing the cost of a new single-family home to a manufactured home. According to the United States Census Bureau, in 2006 the average cost of a manufactured home was $64,200 ($40.13 per square foot) and the average cost of a single-family home not including the land was $225,927 ($91.99 per square foot)[27].

- Construction Waste is Reduced – Leftovers from the cutting of raw materials can typically be reused for the next home being built. The processing of raw materials is done with multiples in mind. Also, materials are no longer left outdoors during storage reducing the likelihood of vandalism, theft or weather damage.

- Construction Quality is Increased – Components and modules are built stronger to withstand transportation to the site and lifting by cranes. Furthermore, the

[27] U.S. Census Bureau, "Cost & Size Comparisons for New Manufactured Homes and New Single Family Site Built Homes," ***U.S. Census Bureau***, http://www.census.gov/const/mhs/sitebuiltvsmh.pdf (accessed November 27, 2007).

factory setting provides a controlled environment where fewer mistakes will be made, tolerances can be improved, and quality control processes are more stringent. The workers all are trained and supervised by one employer, minimizing the conflicts and mistakes that typically occur within the contracted labor system of stick-built construction. Factory construction also allows for a more consistent level of self-inspection and quality control. The higher precision of factory built components also results in a tightly constructed building that is more energy efficient.

3.3. The Manufactured Housing Industry

Prefabrication in home construction today lies predominantly in the Manufactured Housing industry, which in 2006 accounted for 7% of all new home construction in the United States[28]. Only ten years earlier, 25% of all new homes built were manufactured homes. A significant reason for this is the affordability factor, since on average they cost half as much per square foot compared to the cost of a stick-built home[29]. Furthermore, the buyer does not necessarily have to purchase land if they already own it or if they plan on living in a manufactured housing park.

[28] U.S. Census Bureau, “Cost & Size Comparisons,” 2007.
[29] Ibid.

Table 3.1. Cost and Size Comparisons for New Manufactured Homes and New Single Family Site Built Homes from 2001 to 2006

New Manufactured Homes						
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Avg. Sales Price	$48,900	$51,300	$54,900	$58,200	$62,600	$64,200
Avg. Sq ft.	1,545	1,590	1,620	1,625	1,595	1,600
Avg. Cost per Sq ft.	$31.65	$32.26	$33.89	$35.82	$39.25	$40.13
Housing Starts and Manufactured Homes Shipments (thousands of units)						
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
New Single Family Homes						
Housing Starts	1,273	1,359	1,499	1,611	1,716	1,465
Percent of Total	87%	89%	92%	92%	92%	93%
Manufactured Homes Shipments						
Shipped	193	169	131	131	147	117
Percent of Total	13%	11%	8%	8%	8%	7%
New Single Family Site-Built Homes Sold (house and the land sold as a package)						
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Price of Package and Derived Land						
Avg. Sales Price	$213,200	$228,700	$246,300	$274,500	$297,000	$305,900
Derived Avg. Land Price	$49,056	$54,560	$62,929	$73,082	$78,219	$79,973
Price of Structure						
Avg. Sq ft.	2,282	2,301	2,315	2,366	2,414	2,456
Avg. Price Per Sq ft. (excl land)	$71.93	$75.68	$79.21	$85.13	$90.63	$91.99

Given the success of the methods of prefabrication employed in the Manufactured Housing industry, it seems logical that traditional housing developers and builders would start to adopt some of their methods. As with most competitive industries today, advancement should be necessary for survival and prefabrication is next logical step in the evolution of construction. However, the construction industry continues to build the same way they have been for decades and likewise the Manufactured Housing industry has settled into a parallel path that doesn't intrude on traditional construction's territory. Instead of remaining content with their role, the Manufactured Housing industry should be challenging traditional construction by expanding into new structural forms, materials, higher density, and urban infill. Some of the reasons for the general lack of prefabrication adoption in home construction are:

- Complex Market – Housing is a complex market because it is more dependent on land and location and less dependent on the quality of the product itself. It is often of the largest single investments most people will make in their lifetime. The local market is a limiting factor, since the labor intensive process of construction is difficult to export elsewhere.

- Economy of Scale – For factory based manufacturing to succeed, there needs to be a steady or increasing demand for the product. Time equals money, meaning that the ideal situation is that the factory is working at max speed and efficiency and the market is purchasing the product at the same rate. Much less risk is assumed if building is done on demand and outsourced to a variety of contractors and subcontractors. Large housing developers and those that are able to build speculatively are generally the only parties who can proceed with manageable risk since they will have enough volume and capital. For everyone else, it is significantly more difficult to establish a factory that will be guaranteed to be selling enough homes to recover the initial investment and sustain a profit.

- Initial Investment – Opening a prefabrication factory requires an immense amount of start-up capital, which is generally a large deterrent regardless of the eventual return on investment. Some of the upfront costs before a single house or building component can be produced include renting or purchasing the facility, acquiring the necessary tools, equipment, and hardware, training the labor force, purchasing the initial stock of materials, and setting up the factory and delivery processes.

- No Impetus for Change – Because of the local nature of how the building industry operates, there has been less competition on a global scale to spur change. Builders are content to build the way they have been for years. The processes and relationships within the industry are familiar and comfortable, making it harder for newcomers to compete with new ideas and construction methods. Likewise, buyers need to demand better construction processes and higher quality products in order for most builders to consider change. If buyers continue to buy homes the way they are built at the price they are marketed at, very little will change. For those doing prefabrication, there has not really been a strong push to expand their practice into the realm of traditional housing development.

- Stigmas – The prefabricated home has a reputation of being cheap, flimsy, low quality, and aesthetically boxy, unoriginal, and limited. The Manufactured Home industry has not done much to improve the latter but the quality is just the same if not better than conventional stick-built homes. The trailer park and manufactured home park also have a poor reputation of being disorderly and maintained poorly, leading many resident neighbors to protest any new developments in the name of property values.

3.4. Architects and Prefabrication

As designers of the built environment, the architect plays an important role in advancing both theoretical ideas on design and construction and the real world adoption of building technology. From an academic and social perspective, architects have been important theorists in the search for affordable high quality housing solutions for the masses. Also, together with engineers, consultants, and contractors, they have directly advanced methods of construction, introduced the use of new materials and systems, and developed new structural forms. There is an amazing amount of creativity and technical innovation in some of the modern buildings we see being erected today.

However, few buildings in the world benefit from architectural design as it is estimated that only about 20% of the developed world's buildings are designed by architects[30]. Even this figure may be generous. Most of these innovations in architecture have not made their way to the realm of housing as architects have had even less success making an impact on residential design, the most fundamental and predominant architecture that everyone can relate to. This is not for lack of trying, but primarily due to the economics of housing. Put simply, architectural design services are often thought of as a luxury and most housing developers or individual clients are willing to forgo the possibility of good design if they can get their drawings stamped for cheaper. Even though the element of design may result in a more useable, energy efficient and aesthetically pleasing home, the average consumer is most aware and sensitive to the initial upfront cost. This common short-sightedness and reduced valuation of design has resulted in the general low quality of typical housing in the United States today.

[30] Davies, 8.

In the general building process today, prefabrication's use is largely separated from the larger scope of architectural design and instead is utilized by contractors and subcontractors for the construction of specific building components. For example, windows and doors are prefabricated units, as are precast concrete panels and steel I-beams. Materials and products for exterior and interior applications are usually purchased from companies who prefabricate them. At an even smaller scale, machine made bricks and sawn lumber can be considered prefabricated. The prefabrication of all these components is a natural extension of industrial development and only a few building components today are built from raw materials on site.

For architects on the other hand, the goal of prefabrication has always been to explore broader and more encapsulating issues of design and construction. Rather than simply plug existing components and products into their buildings, they want to utilize concepts of prefabrication to design proprietary building systems and construction processes. They want to design all the components that make up their building as well the assembly lines that are used to create them. Generally their efforts are for a good cause, whether it is to address issues of providing mass affordable housing for the working class or pushing building technology by exploring new fabrication machinery and techniques. But again, industries that produce factory-made homes do exist, and yet few architects are involved. Colin Davies provides a reality check by stating:

> "Although we think of architecture as being in some sense in charge of the activity of building, for 150 years or more the prefabricated house has managed perfectly well without architecture's guidance. Situated outside the architecture field, it has cheerfully ignored architectural law. The strength of the prefabricated house lies in its popularity, its cheapness and the industrial base from which it operates. These are precisely the areas in which modern architecture is the weakest. Modern architecture is unpopular, expensive and divorced from industrial production. That is why whenever it has tried to extend its field to

> include the territory of the prefabricated house it has failed and been forced to retreat[31]."

Another difficultly is mentioned by Mark and Peter Anderson:

> "Houses in particular are an important engine of economic expansion in many parts of the world and respond to and initiate forces far outside the immediate realm of design or even the desires of homebuyers, much less the best interests of society as a whole in imagining how to make good places for people to live… the complexities of this relationship within the design process leads back to overly simplistic prefabrication approaches overly focused on detailing and manufacturing process without acknowledging the bigger picture[32]."

With this in mind, it proves useful to look at what has happened in the past as prefabrication began to emerge as a concept in architecture and construction. Many architects have tried to design prefabricated homes with the hope of their designs becoming a widespread solution to housing, but few have succeeded.

3.5. Prefabrication in the Past

The following background information will provide selected accounts of prefabricated housing efforts from both architects and the housing industry. This will give a better perspective of why architects have traditionally failed in the realm of prefabricated housing and also lead into identifying new opportunities for architect involvement.

Although there had already been many examples of prefabricated housing construction in the past, the concept of prefabrication as a potential significant paradigm shift in the way homes are built did not enter the modernist consciousness of architects until the early 1900s when Le Corbusier compared automobile, ship, and airplane construction to

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[31] Davies, 7.
[32] Anderson, 14.

the future of housing construction in a 1919 essay titled "Mass Production Houses[33]." Le Corbusier was perhaps the most important and influential modern architect of the time and he challenged architects and builders to rethink the construction process, and to utilize the industrial and factory assembly processes of the era to create housing for the masses. He wanted architects to open up their minds to new construction methods and wrote, "Everything is possible by calculation and invention, provided that there is at our disposal a sufficiently perfected body of tools, and this does exist[34]." The home of the future that would help solve the problematic housing crisis of his time would be the mass-production house or "House-Machine," which he characterized as "healthy (and morally so too) and beautiful in the same way that the working tools and instruments which accompany our existence are beautiful[35]."

Le Corbusier's own early proposals, like the Maison Citrohan (1920) and Immeubles-Villas (1922) were focused on the standardization of industrial housing based components rather than having entire modules or volumes of the housing built in the factory. Although his proposals were intended to be factory produced, they ended up being hand crafted and quite expensive when actually constructed[36]. While Le Corbusier's original vision still rings true today and has inspired architects to pursue mass produced and prefabricated housing design, his focus at the time was to promote the use of factory made standard materials that were produced by the modern industrial processes of the time. In his own designs, he had not yet ventured into factory produced modular or panelized prefabricated construction.

[33] Allison Arieff and Bryan Burkhart, *Prefab* (Salt Lake City: Gibbs Smith, Publisher, 2002), 20.
[34] Corbusier, 266.
[35] Ibid., 13.
[36] Davies, 16.

Figure 3.6. Sketch of Le Corbusier's Immeubles-Villas Project

Walter Gropius, the founder of the Bauhaus school, was another important architectural figure that attempted to succeed in prefabrication in the areas where Le Corbusier had not explored. After three decades of calling for the industrialization of housing and exploring how homes could be prefabricated, Gropius, along with fellow German countryman Konrad Wachsmann, finally got the chance in 1942 to setup a commercial enterprise to produce factory-made housing in the United States. Their company General Panel Corporation was funded by loans from the National Housing Agency and investors in New York and was setup to deliver a minimum of 10,000 componentized prefabricated "Packaged Houses" a year. The walls, partitions, floors, and ceilings of the homes were assembled from variations of the same basic panels and Wachsmann had designed an innovative jointing system that allowed two-, three-, and four-way connections between the panels. Unfortunately, despite Gropius' influence and Wachsmann's ingenious system, General Panel Corporation failed to setup their operations in time for the end of the war and then failed again in a second attempt based in California. The reasons of failure were numerous, including a divided management structure operating from New York and California, financial difficulties, and

Wachsmann's continuous tinkering with his connection system which led to four redesigns[37]. Furthermore, its failure cannot be blamed on the market, as more than 200,000 prefabricated houses were built in the World War II years by more than 70 companies. In the history of architectural prefabrication efforts, it seems discouraging that Gropius and Wachsmann were not able to make more of their well designed and well funded effort.

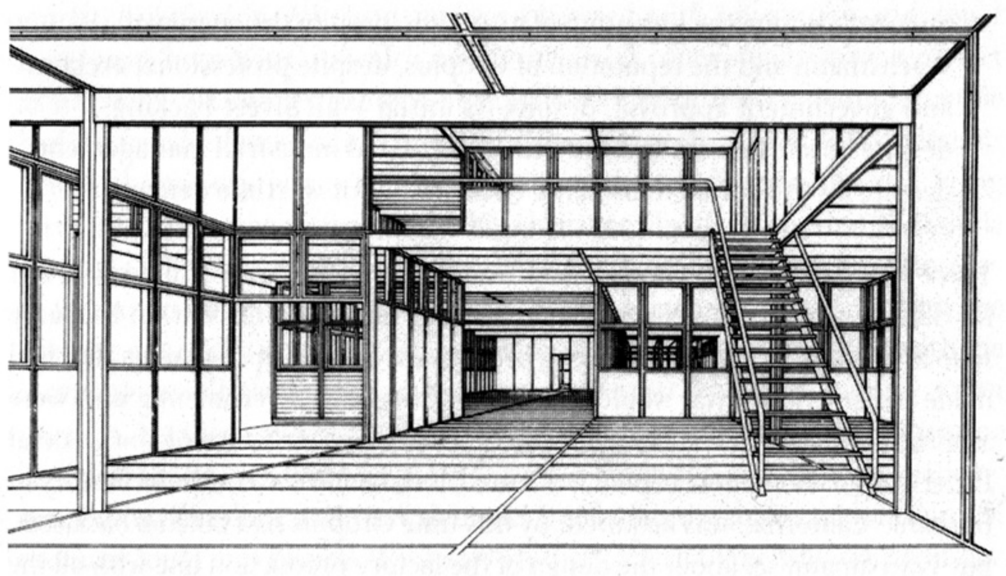

Figure 3.7. Sketch of Packaged House System by Walter Gropius and Konrad Wachsmann

Buckminster Fuller, the inventor, engineer, and architect best known for inventing the geodesic dome, was himself responsible for putting the brakes on his post World War II prefabricated housing effort, the Wichita House. This house was based upon three designs Fuller had produced and patented starting in 1928[38]. The first design was the Dymaxion home, a hexagonal metal house based around a central mast with suspended

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[37] Gilbert Herbert, *The Dream of the Factory-Made House* (Cambridge: The MIT Press, 1984), 309.
[38] Davies, 27.

tension cables holding up the roof and enclosure. The second design was the Dymaxion bathroom, a prefabricated bathroom pod that could be deployed in various buildings. The third design was the Dymaxion Deployment Unit, a circular portable house that the U.S. Army had been using as radar operating huts. The Wichita House brought these three ideas together and could be completely prefabricated in converted aircraft factories. The design itself was the most technically advanced home design at the time with an innovative and ultra efficient lightweight structural system and an aerodynamic circular form that reduced wind resistance, reduced heat loss through the exterior envelope, and increased ventilation through the home. The exterior enclosure was made out of the same alloy as aircrafts. The entire house could be packed onto a single truck and a team of six men would only need one day to assemble it on site.

Figure 3.8. The Dymaxion Home by Buckminster Fuller in the Henry Ford Museum

In 1944, he began working with Beech Aircraft in Wichita, Kansas to transform their aircraft factory into a postwar home production factory. Once the war ended and the marketing for the home gained momentum, they were able to register 3,700 orders for the $6,500 home. However, like the Packaged House, the factory was not quite ready for production and needed an additional $10 million to continue. At this point, the money probably could have been raised based on all the marketing attention the design had received but Fuller, given full veto rights on design issues, decided for unknown reasons to back off the project[39]. Eventually, the lengthy delays caused by his hesitance to proceed caused those involved to lose confidence and the company was liquidated after only building one Wichita house.

Figure 3.9. Charles and Ray Eames Case Study House

Several other important architects during this time explored the potential of prefabricated housing. Frank Lloyd Wright theorized and wrote about the standardization of room-size units within a house, so that homes could be flexibly built by assembling a combination of room units depending on the needs of the family. The closest he came to actual prefabrication was with his Usonian houses, where he developed a standard controlling 4 by 2 feet system that controlled the dimensions of all components of the house. Jean Prouve, known for designing structural frames and cladding systems, worked with the

[39] Davies, 29.

French government to develop cheap, experimental, and prefabricated houses. He was well equipped to take on this task because his headed a workshop of 200 people producing furniture, architectural components, and small prefabricated buildings. However, the project was abandoned after the initial order. Charles and Ray Eames' house for John Entenza's famous "Case Study Houses" was designed so that the components were all off-the-shelf mass-produced parts that could be ordered from manufacturers' catalogs. The idea was never developed further and like many home designs that claim elements of prefabrication, there was never the true intention of taking it to production. Prefabricated modular and capsule architecture on a larger scale was explored in the 1960s and 1970s, most famously by Moshie Safdie in his project Habitat Montreal for Expo 67 and by Kisho Kurokawa in his Nakagin Capsule Hotel in Tokyo. Again, these were one-off experiments and neither were truly intended for mass production or failed to obtain funding for future development. Perhaps the failure of architects to play a lasting role in the field of prefabricated building is due to a lack of understanding and commitment to the non-architectural production aspects. Mark and Peter Anderson state:

> "Prefabrication is simple to understand conceptually and not so difficult to achieve technically. It is primarily an issue of investment and organization, which is a disappointing recognition for most architects, who most typically lack capacity for either, and are more interested in pursuing the concept, the space, the form, the innovative details[40]."

[40] Anderson, 9.

Figure 3.10. Habitat 67 by Moshie Safdie (left) and Nakagin Capsule Hotel by Kisho Kurokawa (right)

Parallel to these architect-led efforts were the companies that experienced commercial success and helped to establish what is commonly thought of as prefabricated housing today. Not being led by architects, most of these prefabricated homes made no claims of advancing architecture and instead attempted to replicate the popular styles of the time at the lowest cost to the customer. They were simply responding to the demand of the times: with the improvement of transportation and building materials and methods, Americans wanted to escape the city, purchase their own piece of land, and build a home in suburbia. Sears Roebuck was among the first companies to successfully sell pre-cut kit homes by catalog in the United States starting around 1908. These kit homes came were delivered as a pre-cut and labeled timber, windows, doors, siding, shingles, nails, and paint. They still required a considerable amount of conventional labor to build but were very popular. Due the success Sears Roebuck was experiencing selling these homes, they soon expanded their operations to provide customers with financing deals that helped to pay for the site and labor. A few years after the depression, they closed down their homes department. However, at their peak they had opened up 48 sales offices in cities all over the Midwest and Northeast and had sold over 100,000[41] homes.

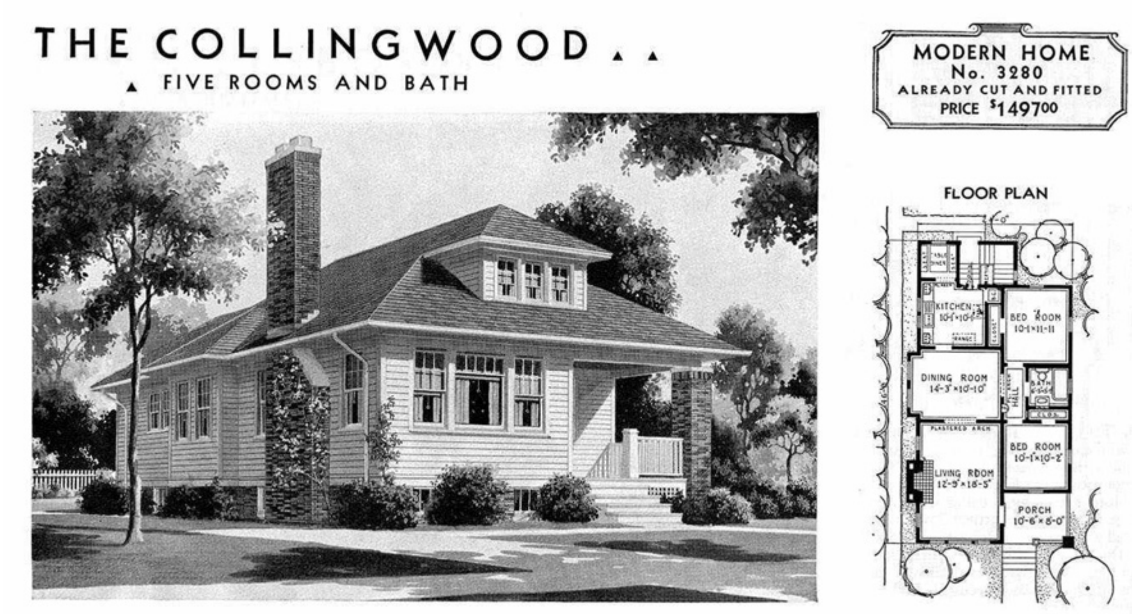

Figure 3.11.   Sears Roebuck Catalog Pre-cut Kit Home

Not all business-led prefabricated housing projects did succeed, as shown by the Lustron house. The idea for the Lustron house was invented by the businessman Carl Strandlund with the help of Architect Morris H. Beckman. The form of the house was rather traditional but the entire house was built from porcelain enameled steel panels, a product that Strandlund's company Chicago Vitreous Enamel Products had patented in 1946. With the help of a $15.5 million loan from the government, he setup a home factory in an old aircraft factory, with the intention of producing the components of the homes using moving assembly lines. Strandlund was able to produce about 2,500 homes but the entire undertaking proved to be a massive failure, largely because of the

[41] Jill Herbers, *Prefab Modern* (New York: Harper Design International, 2004), 16.

complicated and wasteful technical design of the house and the out of proportion investment in factory machinery[42].

Figure 3.12. Lustron Home in Toledo, Ohio

Prefabricated modular construction got its jump start in 1933 during President Roosevelt's "New Deal" Tennessee Valley Authority project. This project was a huge effort to build dams along the Tennessee River to generate electricity to help modernize a generally poor region. A housing difficulty was created due to the large workforce needed and the logistics involved in moving and housing workers at new sites as work progressed. The solution was to develop finished and furnished boxes that could be connected together to form larger units and disconnected again when it was necessary

[42] Davies, 59.

to move them to a new site. These modular buildings were the predecessor for the successes of the mobile home and modular manufactured housing industries.

Trailer homes and mobile homes were gaining respectability in the early 1940s as temporary housing for workers and the military but were soon declared substandard for worker housing in 1943 by the National Housing Agency. One of the primary problems was the limitations of the 8 foot wide road restriction, which made it impossible to accommodate a corridor, meaning one had to walk through other rooms. However, in 1954, Elmer Frey, the president of Marshfield Homes decided to buck convention and built a 10 foot wide trailer home. A more permanent mobile home soon developed, where special permission needed to be obtained to go on the road and the chassis and wheels were just a way to move the home from factory to site. Five years later, the 12 foot wide trailer home was introduced and ten years after that the maximum 14 foot wide trailer had surfaced. By 1968, mobile homes accounted for 25 percent of all single-family homes in the United States[43].

From here, the industry begin to split into those interested in continuing to build truly mobile homes that could be used for regular travel, those interested in building semi-permanent mobile homes that looked like homes but could mobilize if needed, and those who wanted to use the technology to build permanent modular homes. The first group became what is known today as the Recreational Vehicle (RV), producing vehicles like the self-propelled Winnebago. The second group became the Manufactured Housing industry. The final group became modular home builders, and more recently architects

[43] Herbers, 30.

are taking a look at modular design as an entry point into the housing market, both affordable and higher.

3.6. Prefabrication in the Present

One explanation why architects are not making a bigger impact on design is the growing divide between the act of design and the act of building. Before the concept of the architect came into being, there was the master builder, a single person who played the role of architect, builder, engineer, and scientist. The master builder controlled every aspect of design and construction and in addition further advancing the field through invention and theory. As building became more technologically complex, specialization naturally occurred and the traditional roles known today were defined. And as these roles became more established, architects began to lose more control of design, especially in simpler projects where their services were no longer necessarily needed. Stephen Kieran and James Timberlake elaborate on this more:

> "It is the builder who now decides how the building will be assembled – the means, method, and sequence of assembly – all of which affect form. The product engineer, through control of the marketplace of manufactured building materials, now decides what products are available for use. The materials scientist, for his part, now decides upon the composition, the physical substance, of those products. This splintering of architecture into segregated specialties has been disastrous. Once, there was a seamless integration of the constituent elements of building through the person of the master builder, who had control over the materials, products, and construction of architecture. Today this is little interaction among these disciplines, particularly between architect and building on one hand and product engineer and materials scientist on the other[44]."

While architecture will not and should not return to the days of master builder, architects need to reclaim some control of the influences and intent of their designs. In order to do

[44] Stephen Kieran and James Timberlake, *Refabricating Architecture* (New York: McGraw-Hill, 2003), 31.

this, they need to actively communicate with or participate alongside the various fields involved in the construction industry today. Several architects in recent years have begun looking at prefabricated modular and panelized construction as a promising opportunity to better integrate design, construction, and material / product development. This has allowed them to develop some high-quality relatively affordable housing designs that are gaining a little popularity in the housing market.

One architect that has capitalized on the growing popularity of modern modular architecture is Michelle Kaufmann, who started her Northern California-based firm in 2002 in response her own housing search, where she felt there was a glaring lack of affordable, sustainable, well-designed homes. Her goal was to make architect designed sustainable homes accessible to more people by employing prefabrication as a method to cut down costs. Her homes are still quite expensive relative to the average cost of housing but they provide excellent value due to their intelligent and energy saving design. All of her home designs incorporate plenty of natural daylight, maximum cross-ventilation, water-saving fixtures, renewable or recyclable materials, non-toxic finishes, and optional photovoltaic, geothermal, or wind generator systems. She currently offers six pre-designed modular homes which typically cost $250 to $275 per square foot[45], not including the cost of the land. Her website delivers a comprehensive look at what is required of a prospective client to build one of her homes, including costs, site preparation, financing, and more. This provides an approach that is reflective of a well organized business, clearly defining what is received for a relatively accurate cost estimate. In September 2006 she purchased a factory in Lakewood, Washington and opened up a construction company called mkConstructs to build her homes. The factory

[45] Michelle Kaufmann Designs, “Costs,” *Michelle Kaufmann Designs*, http://www.mkd-arc.com/homes/costs/ (accessed November 30, 2007).

produces home modules that can be delivered to Washington, Oregon, California, Colorado, and Hawaii. As of November 2007, Kaufmann has built 21 homes, with over 75 additional homes ordered and in the pipeline. Her goal is to build 10,000 homes within the next 10 years[46]. With her approach to high-end sustainable design at a reasonable cost through the use of modular prefabrication, Kaufmann is in tune with a growing social and environmental consciousness that is driving the popularity of green consumer products like hybrid cars.

Figure 3.13. Images of the Glidehouse by Michelle Kaufmann

Interested in developing a prototype for a mass producible home and inspired by the architecture of Mies van der Rohe, architect Rocio Romero took the concept of prefabricated kit housing and applied a thoroughly sleek modern look. The result was

[46] Michelle Kaufmann Designs, "Press Kit," *Michelle Kaufmann Designs*, http://www.mkd-arc.com/dev/img/products/thumb/MKD_PressKit.pdf (accessed November 30, 2007), 12.

the LV Home, a 2 bedroom 2 bathroom 1,150 square foot home which was originally designed for her mother in Chile. The kit is a combination of wall panels, floors, roof framing, assembly tools, and instructions, all shipped to the customer's site on a flatbed truck. The materials are only enough to build the shell and does not include windows, roofing material, or exterior decks. No contracting services are provided and the buyer can either act as their own contractor or hire a local one to help them assemble the kit. The kit is a mere $30,000 for the standard LV Home kit, but after shipping, foundation, and finishing costs, it will average $120 per square foot, not including the land. Larger versions of the LV Home are also available. Like Kaufmann, Romero's website contains detailed information on the steps necessary to purchase and build the home. The kits are produced near Perryville, Missouri and have been shipped as far as Kauai, Hawaii. Romero markets her product with the terms "simple, quality, green, and space," and the LV Home provides an elegant, affordable high-quality alternative to typical kit homes.

Figure 3.14. Images of LV House by Rocio Romero

In 2002, *Dwell* magazine, one of the most vocal promoters of the modern prefab era invited 16 architects to design prefabricated homes in a competition where the winner would be teamed up with a manufacturer to execute their design. Several notable architects and firms were invited such as Ralph Rapson, Marmol Radziner, and Anshen + Allen. As in the past, the challenge of solving the issue of prefabrication generated some very interesting ideas including the use of new modern materials, standardized components, shipping containers, digital fabrication, and more. The winners of the competition were Resolution: 4 Architecture, a New York firm whose entry aimed to bring mass customization to factory built modular homes at a reasonable price. The major idea was that the modules could be rearranged to meet the program of the clients without incurring the same costs of a custom designed home. Joseph Tanney, one of the firm's two partners states, "It's impossible that one home is right for everybody. Modern Modular is about establishing a system that can be modified for each individual client[47]."

[47] The Dwell Home, http://www.thedwellhome.com/winner.html (accessed November 30, 2007).

Figure 3.15. Images of the Winning Entry for the Dwell Competition by Resolution: 4 Architecture

Most of the current prefab movement in the United States is still focused on single-family homes. However, it is important to look at larger scale prefabricated multi-family housing projects to realize the true potential of prefabrication technology. One such example can be found in London where in 2002, the architecture firm Cartwright Pickard designed Murray Grove, an innovative affordable multi-family housing project. The building is composed of prefabricated light steel framed boxes that are stacked on top of each other to create a five-story 30 unit complex. It was commissioned by the Peabody Trust, a London housing association that pushes affordable, sustainable housing. There are two types of units: one bedroom apartments composed of two modules and two bedroom apartments composed of three modules. The developer and architects teamed up with the local firm Yorkon, a large firm that specializes in off-site construction and manufacturing, particularly modular construction. To construct Murray Grove, the units with their finished interiors were built in Yorkon's factories, trucked to the site and then lifted into position by a crane. It only required ten days to transport and lift all the modules into place. However the site built components such as the decks, balconies, stair tower, roof, and external cladding took twelve weeks to install and the cost of the building actually ended up being slightly more expensive than a similar traditionally built one[48]. Regardless, the project was very well received and won many awards for its innovative design that expresses its modular construction.

[48] Davies, 180.

Figure 3.16. Murray Grove Housing Project by Cartwright Pickard

While recent trends in architect led prefabrication are gaining momentum, some think this is just a passing fad. Witold Rybczynski, a journalist for Slate magazine argues that "the current vogue for prefabs is more about industrial chic than affordability.[49]" Many of the projects he cites are those made popular by magazines such as Dwell and furthermore they are touted as the "future of American housing" in The New Yorker.

[49] Witold Rybczynski, "The Prefab Fad," *Slate Magazine*, http://www.slate.com/id/2171842/fr/flyout (accessed November 30, 2007).

Ultimately, Rybcynski feels that modern prefab is another passing phase in architectural history and that the much cheaper, established, and traditional-looking modular and manufactured housing industry will continue to prevail as the option for those searching for affordable, new, single-family homes. These traditional prefabricated home factories run by developers and builders have also been gaining popularity due to recent events and economics.

Because they are built to withstand the rigors of the road, modular homes are also gaining popularity as affordable hurricane-resistant homes. In the rebuilding effort on the Gulf Coast after Hurricane Katrina, modular homes are offering a cheap, quick, but high-quality, hurricane-resistant way for communities to rebuild. Furthermore, with the high demand for local builders and contractors in the area, modular construction allows labor to be pulled from other regions rather than contributing to the local strain on labor resources. Safeway Homes, a modular housing builder in Jackson, Mississippi sells homes that can withstand high winds for the low cost of $58,000[50], not including land. The homes are delivered as two halves and a roof and like most modular homes, they are craned into place.

Several developers are also starting to utilize modular construction to speed up their housing developments. Although their homes may not have the same design quality as architect designed homes, developers are typically the best suited to incorporate modular prefabrication into their construction process since they own land and have enough volume to reach the needed economy of scale. In Hawaii, Westpro Holdings LLC has been building steel-framed modular and panelized homes on the Big Island. In

[50] Leslie Eaton, "Katrina Victims Find a Solution: Modular House," *The New York Times*, January 6, 2007, http://www.nytimes.com/2007/01/06/us/06modular.html (accessed November 30, 2007).

2005, they setup a $2.5 million factory near Honokohau Harbor and began hiring over 100 people to build the homes, most without previous construction experience. That they could hire inexperienced workers to build the components of their homes is a key advantage of factory prefabrication. Since the production is akin to a manufacturing assembly line, workers only need to be trained in particular skills and can be hired at a lower cost. The 1,215 square foot modular homes Westpro offers can be built in the factory in 30 days and are delivered to the site in two modules[51]. They cost about $340,000 which is about half of what an equivalent stick-built house might cost in the area.

Although they have transformed the process in which homes are built, delivered, and assembled, there have been few innovations in the actual component construction of the current crop of modular and kit homes. Most builders and architects continue to design with traditional wood frame construction since it remains the cheapest method to build. Some firms have adopted Structural Insulated Panels (SIPs) as an alternative but for prefabrication to truly achieve its potential in our technologically advanced era, more needs to be explored. The next section will look at emerging ideas and technologies that may transform the way off-site construction and prefabrication is done in the future.

3.7. Prefabrication in the Future

In order to take prefabrication to the next level, it is important to look critically at the current context in which it is succeeding, beyond the obvious benefits of factory made construction. What are the factors differentiating today's methods of prefabrication from

[51] "Big Island Prefab Homes Going Up," *Honolulu Star-Bulletin*, November 9, 2005, http://starbulletin.com/2005/11/09/news/story09.html (accessed November 30, 2007).

those of the past? How can architects build upon these new elements of prefabrication to make it a more lasting and influential part of design and construction?

In 2004, Stephen Kieran and James Timberlake coauthored a book titled *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*. The book was sponsored by a Research Fellowship awarded to them by the College of Fellows of the American Institute of Architects in 2001. In their book, they examine the design and construction technologies and processes currently used in the building industry and then propose that architects and builders need to rethink the construction process to take advantage of modern advances in manufacturing, information sharing, and mass customization. They argue that today's architects have relinquished responsibility for assembly, product development, and materials research, resulting in segmentation between design and construction that inhibits advances in the building industry. Like many architects promoting prefabrication, they say that the construction industry should look to the automobile, aerospace, and shipbuilding industries for models of efficient and progressive manufacturing processes.

The message of *Refabricating Architecture* is comparable to Le Corbusier's *Towards a New Architecture*, written almost a century ago, in that it is a modern day call for architects to take advantage of the technology that is rapidly evolving around them to bring architectural construction up to date with the times. While not as wide-reaching as Le Corbusier's manifesto, Kieran and Timberlake effectively present many of the same ideas in the context of modern technology and developments. They do not offer extensive details or instructions on how to implement a change in the relationship between architectural design and construction through prefabrication but they do present several important big ideas that suggest that the world today will be more receptive to the need for prefabrication. The following are some of their ideas for the new future of factory construction and prefabrication in the building industry:

- Mass Customization – According to Kieran and Timberlake, "the difference today that will enable modularization and mass production to succeed is its ability to be customizable[52]." Mass customization has become a buzz word in modern prefabrication and they believe that it is the single most important change that will allow prefabrication to succeed in the modern world. Technology has allowed industrial processes to rely less on quantity to be cost effective. Rather than select from a set of completed products produced by the manufacturer, the customer now has the ability to participate in determining a unique set options for the product they eventually purchase. Thus factory produced housing no longer means that everyone gets a similar functioning and similar looking house. This will help generate more interest and mass appeal for the higher quality and cost savings that prefabrication provides. One of the analogies they point to is how Dell has transformed the way personal computers are purchased and built, where each computer is tailored to each customer but production costs are still minimized.

- New Materials – There is a current explosion of new materials being created, but there is little or no communication between architects or contractors and the material scientists that are developing these materials. This was fine when materials were limited to what nature offered and there was a universal

[52] Kieran, 111.

understanding of their properties, but with new categories of synthetic materials being invented, the lack of communication creates a lost opportunity. Kieran and Timberlake believe material scientists and product engineers should be integrated into the process of building design, which can lead to new uses and innovations of materials in buildings beyond pure aesthetics. This is important in architecture because historically new materials have influenced new forms and methods of construction.

- Process Engineers and Integrated Collaboration – The increasing segregation of architects, contractors, material scientists, and product engineers has resulted in a lack of collective intelligence among these integral parts of the building process. In the current model, there is little communication between disciplines and most of it is in an unequal hierarchical relationship where one discipline hires the other rather than true democratic collaboration. First, Kieran and Timberlake propose more crossovers between disciplines, where "producers engage in design, and designers engage in production[53]." Next the role of the process engineer emerges, producing interactive tools that allow disciplines to communicate and exchange information in real time throughout the entire project. This integrated collaboration results in a higher quality comprehensive project for less cost and time. This paradigm shift has already happened in the airplane, ship, and car industries with connectivity websites and enabling software helping connect the various disciplines involved. Whereas Le Corbusier promoted the use of the assembly lines used in these industries as the method for increasing quality and reducing cost and time in architecture, Kieran and Timberlake

[53] Kieran, 13.

propose that the process engineering used by these industries is the model the building profession should attempt to emulate.

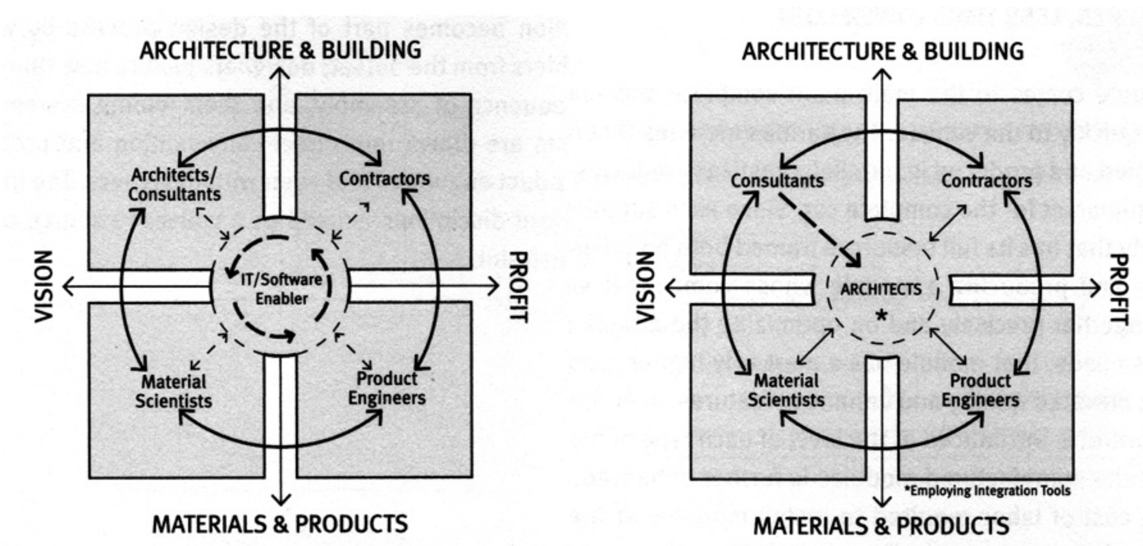

Figure 3.17. Diagram from Stephen Kieran and James Timberlake Illustrating IT/Software Linking Disciplines (left) and Architects Assuming the Linking Role (right)

In order to begin taking their ideas in practice, Kieran and Timberlake's architecture firm KieranTimberlake developed a prototype prefabricated house in 2006. The Loblolly house was a perfect opportunity to test their theories since Kieran was also the client. The house utilizes a host of ideas from prefabrication, including the use of standardized components, a panelized "cartridge" system, modular components, and more. Approximately 60 to 70 percent of the components were factory-built for this prototype and if the house were to become commercially available, they would like to push it to 80 to 85 percent which would bring the price down to about $250 per square foot[54]. The only parts of the building that were built on-site were the wood piles, an outdoor staircase, the bamboo flooring indoors, and the cedar plank siding.

[54] Clifford Pearson, "Loblolly House, Maryland," *Architectural Record*, April 2007, 146.

The floors and walls of the house are built from a custom component-based design, where floor or wall “cartridges” of the house can be configured in a variety of ways and can be easily bolted together or unbolted for disassembly. The cartridges are simply conventional wood two-by-fours sandwiched between two sheets of plywood and are categorized into “smart” and “dumb.” Smart cartridges are used for the floor and have radiant heating coils, electrical distribution and outlets, cooling microducts, and insulation. Each cartridge plugs into main service channels that run across the entire floor. Dumb cartridges are used for the walls and roof only contain insulation. The other prefabricated components of the house include an off-the-shelf aluminum structural frame, an exterior rain screen built from uniform cedar panels, and factory-built bathroom and kitchen modules.

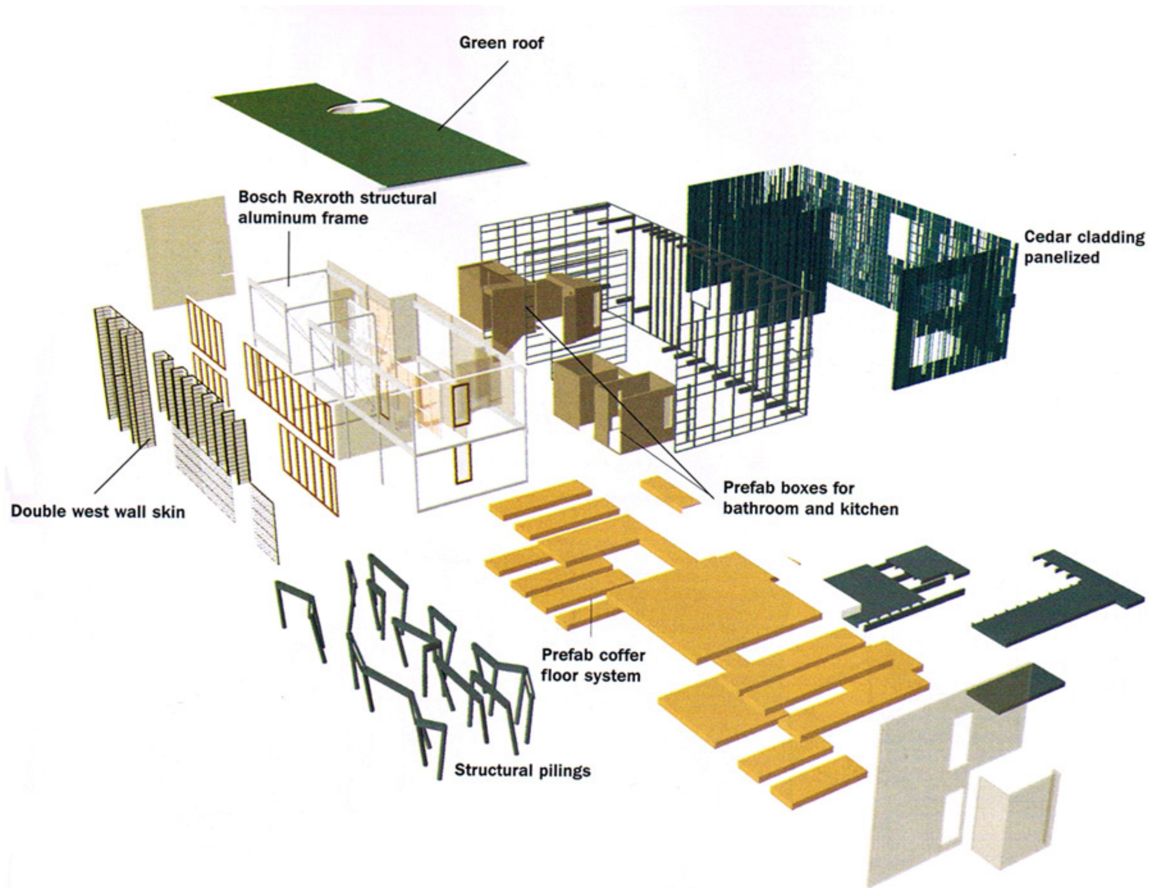

Figure 3.18. Diagram of Building Components in Loblolly House by KieranTimberlake

One of the most vital and challenging parts of putting their ideas in practice was the establishment of an efficient supply chain to prefabricate all the components. KieranTimberlake chose to partner with Bensonwood, a New Hampshire based timber-frame house company, as a supplier, fabricator, and assembler. Arena Program Management served as the construction managers. Using the Building Information Modeling (BIM) capabilities of Autodesk Revit, they were able to general a precise model of the design that stored detailed information such as dimensions, materials, and suppliers / fabricators within each of the various elements of the building. The virtual building model served as the main point of information exchange throughout the supply chain. Enough fabrication details and tolerances were included in the model for the fabricator so that time consuming steps like the shop drawing process could be sidestepped. All building components were tracked with bar codes that were also stored in the Revit model so that the on-site assemblers knew where to install them. According to Kieran, "Parametric modeling was the breakthrough that allowed us to take components manufactured at various places off-site and bring them together with a high level of precision on-site[55]."

Figure 3.19. Loblolly House by KieranTimberlake

As seen by KieranTimberlake's prototype home, the future of successful prefabrication is much more complex than simply taking wood framed construction indoors. Through a holistic approach of design, procurement, fabrication, and assembly, an intelligent and integrated process or prefabrication can be established. The combination of a hybrid of prefabrication techniques, a designed supply chain, and efficient use of a central building model provides a well researched future model for prefabricated buildings.

[55] Pearson, 145.

One of the significant technological enablers of the concept of mass customization in architecture is the advent of digital design and manufacturing. The combination of advanced 3d modeling programs with Computer Numerical Controlled (CNC) milling machines has given architects a direct link to fabrication. This allows designers to precisely fabricate unique and complex forms over and over without incurring high fabrication costs. Since the digital model controls the fabricating machine rather than each component being crafted by hand, architects can now essentially fabricate whatever they can draw and model on the computer. This opens up a world of new design possibilities. This has already been seen in high profile architectural projects like the recent work of Frank Gehry, but has not yet made a large impact on the residential market.

One of the more recent examples of digital fabrication on a smaller scale home is Steven Holl's Turbulence House in New Mexico. For this project, Holl took an initial water color concept sketch and brought it into a 3d modeling program. He then teamed up with A. Zahner Company Architectural Metals, the Kansas City, Missouri sheet-metal fabricator that has worked on most of Frank Gehry's projects, to develop an enclosure and structural system that when pieced together would compose his envisioned form. Together, they came up with a rib and stressed metal skin system that combines structure and enclosure. Using the 3-D model, they were able to have the fabricating machines precisely cut the shapes necessary to produce the parts for 31 unique galvanized aluminum metal panels that when pieced together on-site would create the house. The flexible aluminum bends across the shaped ribs to produce the rounded compound curved forms and to give it structure. Each of the completed panels was designed with shipping in mind, limiting the maximum width with of any panel to eight feet[56]. Once on site, only six days were required to assemble the 31 panels.

Figure 3.20. Images of the Turbulence House by Steven Holl

The end result is a uniquely shaped home that resembles the tip of an iceberg. Rather than to try and build the house conventionally, which would have been nearly impossible given the complexity of the form, the digital design and fabrication process allowed Holl to skip the typical construction documentation process and have his design directly fabricated from his 3-D model. With the technologies being used in prototype homes like the Turbulence House, prefabrication is beginning to shed previous limitations of what was possible. This house would not be possible to manufacture without first digitally prefabricating all the components off-site at A. Zahner Company's factory.

[56] Herbers, 117.

A more traditional looking modern home completed with the same digital fabrication technologies is the Digital House by the architects Bell Travers Wilson of London. Funded by the London Development Agency to investigate ways to improve traditional house building through digital technology, they spent two-and-a-half years of research and development to create the Digital House. Whereas the complexly shaped aluminum panels and ribs that Holl prefabricated required the help of a sheet-metal fabricator, Bell Travers Willson simply cut the components of the Digital House out of sheets of plywood using their own CNC router. Like the Loblolly house, they employee a system of cartridges that is used for the floors and walls. These cartridges are arranged and connected together to generate a customizable layout. To create the cartridges, they first model all the parts of the cartridge in high detail using the 3-D modeling program Autodesk 3ds Max. The 3-D model is then sent to a CNC router where the parts are cut quickly and precisely and then assembled by hand. The resulting cartridges are light enough to be handled by one person, so that piecing together the house does not require a crane or other heavy equipment. Once in place on the construction site, the cartridges are blow-filled with recycled newspaper for air tightness and insulation that doubles the requirements for homes in London.

The system of fabrication and assembly that Bells Travers Willson has developed allows for components to be built fast and accurately without the need for skilled contractors. When cutting all the parts, all the screw holes and connections are also included so that building the house is like assembling a piece of furniture. Also, because the cartridge parts are cut by the CNC router based on a 3-D model, it is easy for them to quickly modify the model and re-cut the parts if they need smaller or larger modules. As far as prefabrication goes, they are not limited to the economic requirements of mass production. They can prefabricate at a low volume without incurring financial losses. Bruce Bell explains, “We have developed this system to exist outside the rules of mass production where repetition and standardization are what govern the cost effectiveness[57].”

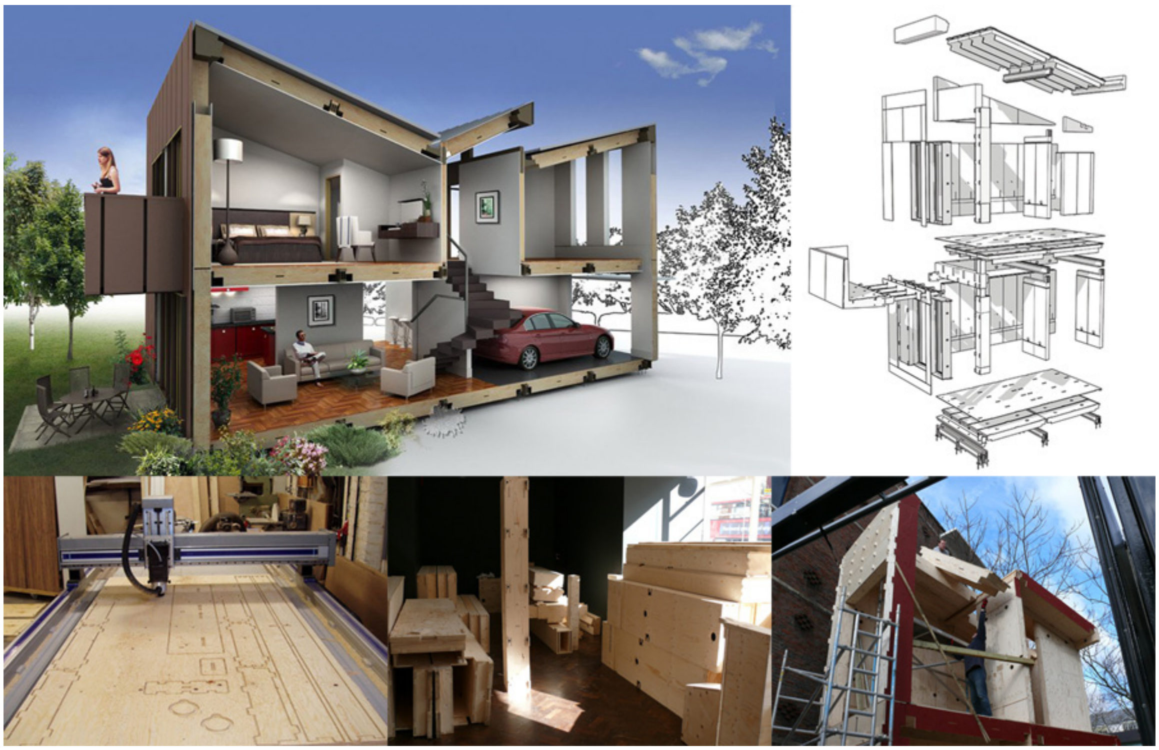

Figure 3.21. Images of the Digital House by Bell Travers Willson

The new ability to mass customize architectural forms and components through digital design and fabrication has been particularly exciting in the use of concrete. Traditionally, prefabrication in concrete means selecting from standardized precast components like columns, beams, and decking or using factory built formwork like insulating concrete forms or reusable aluminum forms. Like most prefabricated building components, the architect is generally limited to what the factories produce. To have

[57] ArchitectureWeek, “Components House,” *ArchitectureWeek*, http://www.architectureweek.com/2007/0425/tools_1-2.html (accessed December 4, 2007).

custom formwork be cost-efficient, the project or budget must be on a much larger scale. However, digital fabrication has allowed architects to generate complex shapes on computer and then cut the forms using CNC milling machines. Custom formwork in low production volumes can now be produced at a significantly lower cost. These new technologies in prefabrication have given architects a greater ability to sculpt and control concrete.

Bill Massie is an architect who has been at the forefront of applying digital technologies to shape concrete. He uses these techniques not to create "affordable" housing but rather to create architecturally interesting custom homes at an affordable price. He is quoted as saying, "I don't think I can reduce the cost of building a conventional building, but I think I can meet the cost of conventional building and make a more extraordinary thing[58]."

His self-designed self-built Big Belt House in Meagher County, Montana is a prime example of this. With the goal of designing a house that truly responded and blended into the site, he directly generated the rolling forms of the house by translating and manipulating a digital topography of the site. Once the house was designed and modeled in 3D software, Massie derived the shapes of the concrete formwork from the computer model. These digital files instructing how the formwork was to be cut were then fed directly into a CNC milling machine, where approximately 1,500 transportable pieces were produced out of rigid foam[59]. The formwork pieces were produced like a jigsaw puzzle so that when transported to the site, they could be easily assembled with

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[58] Karrie Jacobs, *The Perfect $100,000 House* (New York: Viking Penguin, 2006), 257.
[59] "Big Belt House," *National Building Museum: Liquid Stone*, http://www.nbm.org/liquid_stone/home.html (accessed December, 6 2007).

less hardware and confusion. With this innovative method of building, he was able to skip construction drawings and directly produce the formwork for the concrete by himself, thus essentially eliminating the need for a contractor. The resulting home is a composition of curves that defies the conventional notion of what a concrete building looks like.

Figure 3.22. Images of The Big Belt House by William Massie

While other architects pursue the limits of what the latest technologies allow them to produce, Anderson Anderson Architects focus on how to incrementally integrate prefabrication practices into the existing framework of the complex construction industry. Although their work is not as eye-catching as some of the previous work shown, they are perhaps better equipped to make a more immediate impact in the future of prefabrication with their comprehensive and grounded approach. Like KieranTimberlake, they offer clear and strong thoughts on prefabrication's role in the future of architectural design and construction throughout their work. Instead of developing unique components or proprietary systems, they search for ways to adapt and integrate already existing components and processes into systems and organizations that can be applied to high-volume production. In their book, titled *Prefab Prototypes: Site Specific Design for Offsite Construction*, they elaborate on their position:

> "Based on past experience, successful progress in construction process will not come from singular innovations or proprietary systems. Architects and

> prefabrication entrepreneurs must first research and understand the construction industry as it now exists and has historically evolved and then focus imagination not just on changes in material and assembly mechanics, but also on looking deeply beyond this into the process, networks, and system logic of the industry as an integrated complexity, to be unraveled piece by piece, understood, renegotiated, and rationally restructured as an effective and realizable whole. A part of this understanding must include a recognition that not all of construction can happen in a factory, that there must always be a role for and an increasing respect for the most complicated part of the process… the attachment of the idea and building to the ground[60]."

Mark and Peter Andersons' rational approach to prefabrication has led them to investigations into a wide variety of prefab methods and materials in their projects. They have worked with panelized 2x4, CNC timber framing, concrete systems, steel framing, sandwich panels, and modular systems. One of the underlying themes behind all their prefabricated projects is the innovative use of existing manufactured components into alternative but logical uses. By successfully executing designs through this methodology, they begin to make a strong case for construction related manufacturing industries to perhaps adapt some of their component product lines for prefabricated architectural use.

In 2005, Anderson Anderson Architecture developed two hillside housing schemes in Seattle, using prefabricated composite concrete structural panels as foundation and retaining walls for the complex sites. The composite panels which combine structural steel tube frames, polystyrene foam insulation, and a thin covering of fiber-reinforced concrete are developed and factory produced by a Canadian company called IHI Corporation. Typically used for industrial structures, the architects worked with the company to adapt the panels into strong, water-tight, underground foundation walls that can be immediately inserted on site as excavation proceeds, thus reducing the usual

[60] Anderson, 18.

complex, dangerous, and time-consuming work involved in casting in-situ hillside foundation and retaining walls[61]. Furthermore, the panels were pre-finished on the interior and had excellent thermal, sound, and fire-resistance properties. This project successfully took a pre-existing manufactured complex material assembly and applied it to very site and function specific use. It was relatively easy for both the manufacturer and architect to adapt the use of the advanced composite panels for a rational and effective use in hillside construction.

Another important area that the Andersons have been exploring is the use of prefabrication and modular design in high-density, urban mixed-use developments. In 2005, they completed three schemes for large urban housing complexes in California, Virginia, and Oklahoma. These projects are as concerned with the process of manufacturing the units as they are with the actual component construction of the homes. For the California project, named the Organic Urban Living Armature (OULA), they envision developing a sustainable two city-block residential community in San Francisco using steel structure and the concrete composite panels mentioned previously in the hillside projects. The panels would be manufactured in Canada, shipped to a staging area in Sacramento where the modular units are constructed, and the trucked to San Francisco for final assembly and finish. This manufacturing and prefabrication process would take an estimated 5 months of offsite work and 3 months of overlapping on-site work to build, which works particularly well in urban cities where it is important to reduce urban disruption and sitework pollution[62]. The Virginia project employs a similar two-block scheme and both employ the use of sustainable urban strategies such as

[61] Ibid., 86.
[62] Ibid., 200.

mixed-use programs, shared community spaces, photovoltaic panels, rain-water catchment, and waste water treatment tanks.

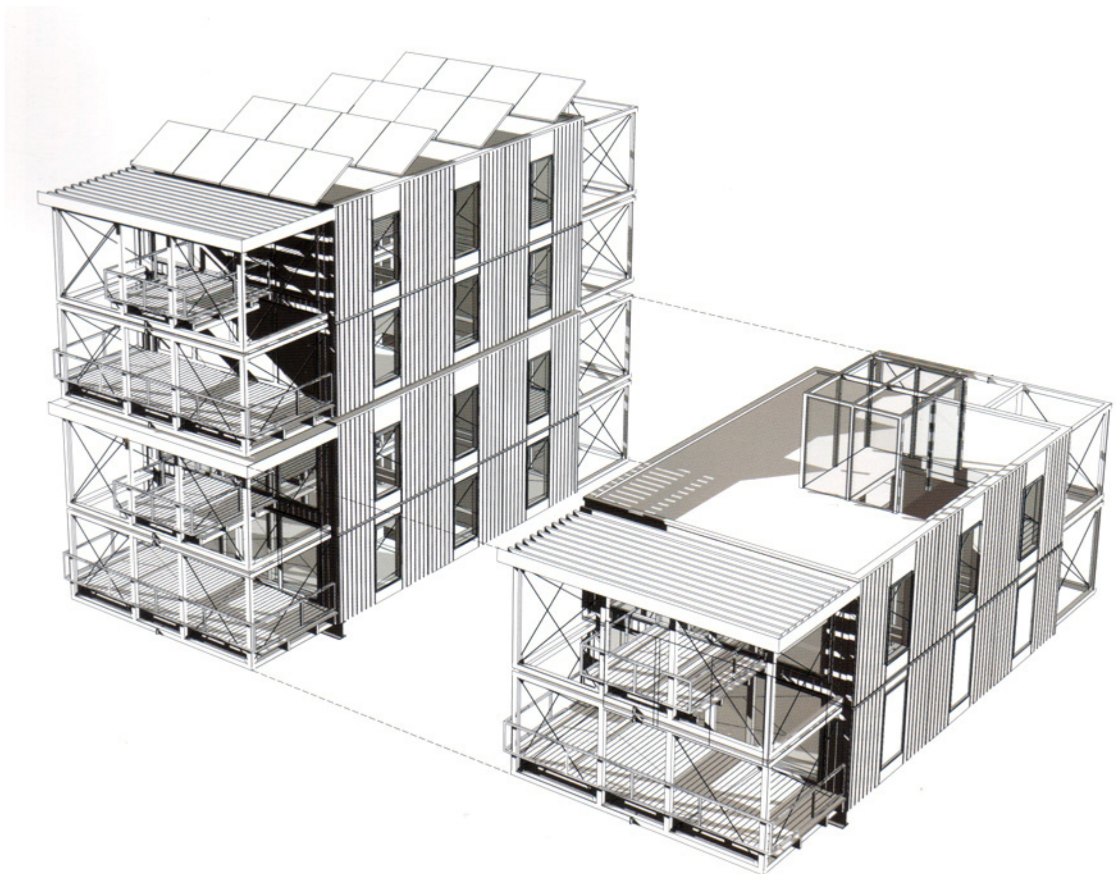

Figure 3.23. Prefabricated Apartment Modules for the Organic Urban Living Armature by Anderson Anderson Architecture

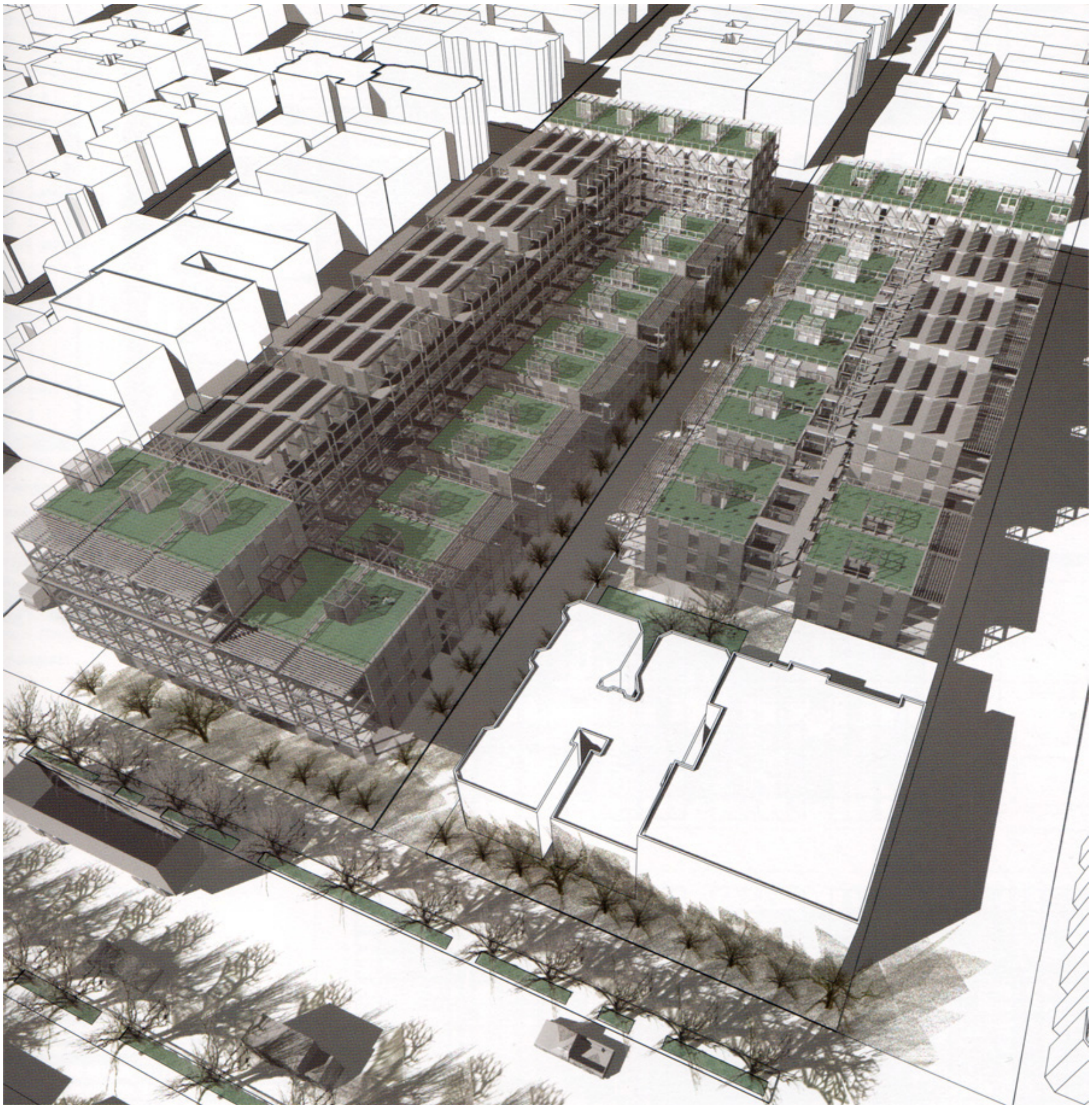

Figure 3.24. Perspective Rendering of the Organic Urban Living Armature by Anderson Anderson Architecture

In the downtown Oklahoma project, Anderson Anderson Architecture takes advantage of the developer's steel fabrication business to develop a detailed steel system that could be easily prefabricated in mass. Furthermore, as part of the urban and financial considerations of the project, they propose that a nearby factory be setup that primarily hires local workers to build the steel components project, which could help produce jobs and inject revenue into the community. While the issue of mass factory production has often been proposed in the realm of prefabricated architecture, in this project the Andersons are proposing to adapt existing establishments and resources while also presenting some sound business and community advantages. This broader view of the role of prefabrication in fields outside of architectural design helps set them up for continued success in their future pursuits of prefabrication.

The Andersons believe that a key component of prefabrication and modularization of products and materials is the process of designing for the reuse of products. While more complex than simply recycling products, they feel that there are "substantial environmental, economic, and even creative socio-cultural benefits that may be obtained from imaginative repurposing, reapplication, and reuse of previously designed and/or previously used products[63]." As important as it is to reduce construction waste during the process of fabrication, it is even more praiseworthy to look ahead to the future and consider how each prefabricated product can been disassembled and reused after its first-use lifespan has ended.

As the above examples have shown, there is an exciting future in prefabrication that lies outside of simply taking conventional construction techniques into a factory setting. This is the direction prefabrication needs to head in order to carve out a more successful and sustainable market since the least expensive way of building is still the most conventional due to a highly efficient system that has been developed around stick built construction for many years. Digital software, technology, and machinery is opening up the door for architects to become highly involved in exploring how the fabrication

[63] Ibid., 253.

process can be more efficient, how new forms and shapes can be generated out of traditional or new materials, and how they can better market their services to clients. Architects are coming up with increasingly creative ways to utilize current technologies and industrial processes to implement prefabricated components in their designs. If architects can effectively educate builders, manufacturers, and the public about the advantages of today's modern methods of prefabrication, they will finally be poised to make a larger impact on housing construction.

4. Key Technologies in Modern Prefabrication

In this chapter, the technologies driving modern prefabrication will be explored and analyzed to provide a better understanding of their potential benefits to architecture and construction. These technologies range from the modern marketing and productizing of prefabricated homes through the internet to the Computer Aided Manufacturing (CAM) technologies behind the modern prefabrication movement.

4.1. Internet Marketing of Prefabricated Housing

Over the past few years, the Internet has opened up the way business is conducted and how products are marketed and sold. The consumer has become increasingly empowered, with a wealth of information available at their fingertips. Smarter consumers will only drive innovation in architecture and construction as they now begin to understand more about the process behind the design and fabrication of buildings. The current movement of prefab modern homes relies on this ability to communicate to prospective clients the various benefits of prefabrication. Where aesthetics was once the primary way a building might initially be judged, the way it is built and its overall performance are now equally important measures to the consumer. The internet has facilitated this transmission of information and architects involved in prefabrication are using it to help dispel the misconceptions about homes built in this manner. Furthermore, taking a cue from the car industry, they are marketing their designs as prepackaged products that can be customized and tailored online depending on the needs and budget of the purchaser.

As described in the previous chapter, architects such as Michelle Kaufmann and Rocio Romero have setup websites where they clearly describe the process of building their designed homes from start to finish. They both offer their homes as either an existing off-the-shelf design or a custom design. Although site specific factors determine the final cost, prospective buyers are able to get an idea of how much a home and the various options might cost them before even speaking to anyone. Furthermore, they can see detailed floor plans and images of what finished spaces might look like. With this level of information at their disposal, architecture begins to crossover from a service to a product. While developers have long taken this approach with the sales of their speculative residential developments, there is often little room to customize or select options. Architects are new to this method of marketing their services, as they have traditionally been commissioned to do custom one-off homes rather than designing speculative buildings to be sold to specific markets of consumers. The internet is providing an accessible and effective medium for the display of their product and the ideas behind the design.

Empowered with this marketing tool and the realization that homes can be sold like any other product online, some have taken the idea of selling homes online to the next level. Steve Glenn, a technology entrepreneur who happens to be an architecture enthusiast, decided to team up with architects Ray Kappe, David Hertz, and KieranTimberlake to design prefabricated homes that could be configured and purchased online. Based in Los Angeles, LivingHomes markets their homes as modern, green, architect-designed, prefabricated homes. The company's goal is to build and sell healthy, luxury homes at lower prices and higher value by employing prefabrication technology in the construction process. Pricing of these semi-custom homes ranges from $180-$250 per square foot, which does not include design costs, permit fees, engineering, transport, installation, or foundation. Additional services can add another $70-$90 per square foot. LivingHomes estimates that their prefabricated construction process saves anywhere from 20% to 40% of the cost of an equivalent stick-built custom home. All of their homes are rated LEED Silver and they offer options such as cistern and water reclamation, photovoltaic systems, solar water heating, home automation systems, environmental home monitoring, denatured alcohol-based fireplaces, and motor-driven window shades.

Figure 4.1. Images of LivingHome by Steve Glenn and Ray Kappe

The LivingHomes website does an excellent job of presenting their product and helping a buyer understand the steps necessary to build a LivingHome. Through their interactive site, they present a proposed schedule which clearly defines to the user how long each phase will take and what will be required of buyer and what tasks they will take care of. Any initial confusion behind buying land, financing the project, and building the project is taken care of in this section of the site. Configuring a potential LivingHome is made a fun interactive experience through a graphical interface that immediately updates selected options in a rendering of the interior or exterior of the house. As options are added and removed, prices are updated as well as detailed information about the building's sustainable qualities. This is an innovative approach to marketing their homes, as the website user can immediately see what a potential home's LEED rating, energy and water savings per year, percentage of environmentally friendly or recyclable materials used, and more. There is also a section of the site where the user can generate a comprehensive estimated budget for a project. The experience is much like visiting a car manufacturer's website to configure the color and other options. In the end, potential customers are able to get a clear picture of what their house might look like, how "green" their house would be, how much it might cost, how long it would take to fabricate and assemble, and the process of financing and getting approvals for the project. All this information is packaged neatly in a website that they can explore freely before talking to a salesperson.

Figure 4.2. Screenshot of LivingHomes Website

For consumers, one of the biggest advantages of modern prefabricated homes is the ability to know in advance what they are getting and how much the house will cost. Architects involved in trying to commercialize and productize the modern prefab movement are using the internet to enhance the home research and buying experience so that users are able to compare homes with greater detail. Home buyers in the future will be expecting this level of detailed information and configuration options when purchasing a home and those architects who have setup comprehensive websites to market their products are getting a head start on reaching out to the sophisticated buyer. Kent Larson, director of MIT's House_n project describes this future consumer and their market demands:

> "The baby boomers, born between 1945 and 1965, control much of the wealth in the U.S. and are the largest purchasers of new homes. Their values are very

> different from those of their depression-era parents who accepted mass-produced homes. Market studies by AARP Research, Roper Starch, and others reveal that boomers are sophisticated consumers who want choice and tailored solutions that closely reflect their values. They are a diverse group who reject the "one size fits all" model. They want homes that can accommodate increasingly complex family activities and work patterns. They want environments that can easily adapt over time as family/financial/health situations change. They want their homes to help them remain productive, connected, healthy and autonomous as they move into retirement. They have ever increasing expectations of the products they buy and want to be assured that they are getting value for their money. They expect full disclosure and immediate information. They want low maintenance materials, systems that can be upgraded without disruption and houses that can readily accept new technologies and services. It is difficult to find even one of these attributes in the generic, mass-market, low-tech offerings of speculative housing[64]."

More for less is being demanded by the future consumer and the presence of internet marketing and widely available information is helping to drive this demand. Traditional architecture services will be hard pressed to offer the same level of information that prefabricated housing architects can easily provide.

4.2. Building Information Model (BIM) Software Systems

Most efforts of prefabrication in architecture have attempted to simulate or compare how the complex but highly-efficient automobile, ship, and airplane industries manufacture their products. Although houses can theoretically be prefabricated in the same manner, building construction has always had some unique characteristics that have prevented it from adopting the same methods of manufacturing. The most significant differences between housing and these other large scale industries are that buildings are site specific and must adapt to a unique terrain, they are typically built to be permanent rather than mobile, they are not produced at the same volume, and they require less technology and equipment to function.

[64] Larson, 63.

Instead of only focusing on how the building industry can adopt the same physical manufacturing processes as these other industries, Kieran and Timberlake suggest that architects pay more attention to the tools and software that drive how fabrication and assembly are planned, designed, tested, and visualized. The most fundamental difference is that the current tools and systems architects use only represent buildings, while in the automobile, ship, and airplane industries the tools model and simulate the vehicles[65]. The final drawings an architect produces for the contractor are flat projections that simply represent the building and must be interpreted by the contractor. Oftentimes, there will be information missing and inconsistencies due to mistakes made during the process of representing a three-dimensional object in two dimensions. On the other hand, modeling simulates the three-dimensional object more accurately, allowing it to be more easily visualized as a larger structure broken apart into sub components. All the joints and other details can be fully modeled in 3-D so that all the various global manufacturers involved in designing or assembling parts of the vehicle know exactly what components are involved and where they belong. Furthermore, each part is embedded with information describing its design constraints and its producer, decreasing the chance of conflicts or mistakes in fabrication or assembly. The way automobiles, ships, and airplanes are modeled in computers fits seamlessly into how they are globally manufactured today.

One of the well-known examples of an architect using another industry's tools to design and fabricate buildings is Frank Gehry's use of CATIA in his practice. CATIA, which stands for Computer Aided Three Dimensional Interactive Application, was originally developed in-house by the French aircraft manufacturer Dassault to help with the design

[65] Kieran, 59.

and manufacturing of the Mirage fighter jet[66]. The software offers 3-D computer aided design (CAD), computer aided manufacturing (CAM), and computer aided engineering (CAE) capabilities for a complete cycle of design, manufacturing, and testing. Using IBM as their main distributor, Dassault's CATIA program soon became the primary software suite used by the automobile, airplane, shipbuilding, and other engineering based industries. In 1992, Gehry designed a woven steel curved three-dimensional fish sculpture for the Vila Olimpica Hotel in Barcelona. The complexity of the form and the need be able to pull apart the various surface components to form the sheet metal led Gehry's team to use CATIA. The software allowed Gehry to precisely model the sculpture so that every point on the fish could be mathematically defined and it also interfaced seamlessly with structural analysis programs[67]. The CATIA model was used by the fabricator, Permasteelisa, to accurately build all the components, detail the connections, and assemble it on site. Gehry continued to use CATIA on future projects, including the Guggenheim Bilbao, his most famous building. He is currently developing an architecture based version of CATIA called Digital Project, under the company Gehry Technologies[68].

[66] "CATIA," *Wikipedia*, http://en.wikipedia.org/wiki/CATIA (accessed December 8, 2007).
[67] Daniel Schodek, et al., *Digital Design and Manufacturing* (New Jersey: John Wily & Sons, Inc., 2006), 42.
[68] "CATIA," 2007.

Figure 4.3. Fish Sculpture for the Vila Olimpica Hotel in Barcelona by Frank Gehry

Building Information Model (BIM) software systems are being developed by software makers to help architecture transition from representation to modeling and simulation. The concept of BIM in architecture is “the general idea of a parametric 3-D model as being the central vehicle for the generation of everything from 2-D drawings, materials lists, other reports, and various kinds of analyses (e.g., cost, structural), and further serving as the primary basis for interactions and information exchange among all participants in the design and building process[69].” These capabilities are already available in existing software such as Pro/Engineer and CATIA. However, these software programs do not offer tools geared towards the profession of architecture. More recently, architectural software suites such as Autodesk Revit, Graphisoft

[69]Schodek, 123.

ArchiCAD, and Bentley MicroStation are now being developed and marketed towards architects and engineers, providing them with new tools to fully parametrically model buildings and embed information within the model.

Due to the long established and conventional contractual processes of delivering 2-D drawings to the consultants and contractors and the ever-present problem of who will pay for the integrated BIM approach, adoption into the mainstream architectural practice has been slow and gradual. However, BIM software is a key tool in making modern prefabrication possible. Since the design, supply chain, fabrication, and assembly are tightly linked in prefabricated architecture, it is essential to have software that can centralize all the necessary information. BIM software can help streamline the entire process by embedding information that identifies which supplier is responsible for the fabrication of a part and how it fits together with the other parts of the building. As mentioned in the previous chapter, in their prefabricated Loblolly house project, KieranTimberlake was able to successfully utilize Autodesk Revit to document their design and exchange detailed information with suppliers and fabricators.

In BIM software systems, 3-D modeling is based on object-oriented parametrically variable components. For example, a door or window object will exist with a defined geometry whose geometry can be altered by the user. Furthermore, this object will know how to behave when set into a wall. For prefabrication purposes, this is useful, as all the building components can be defined as objects and variations of the same objects can also be easily generated. Fabricators will then know exactly how all the components are modeled and how they fit into the overall building. The digital representations of the components, with its embedded geometry defining its shape and form, can then be processed and sent to CNC milling machines for fabrication.

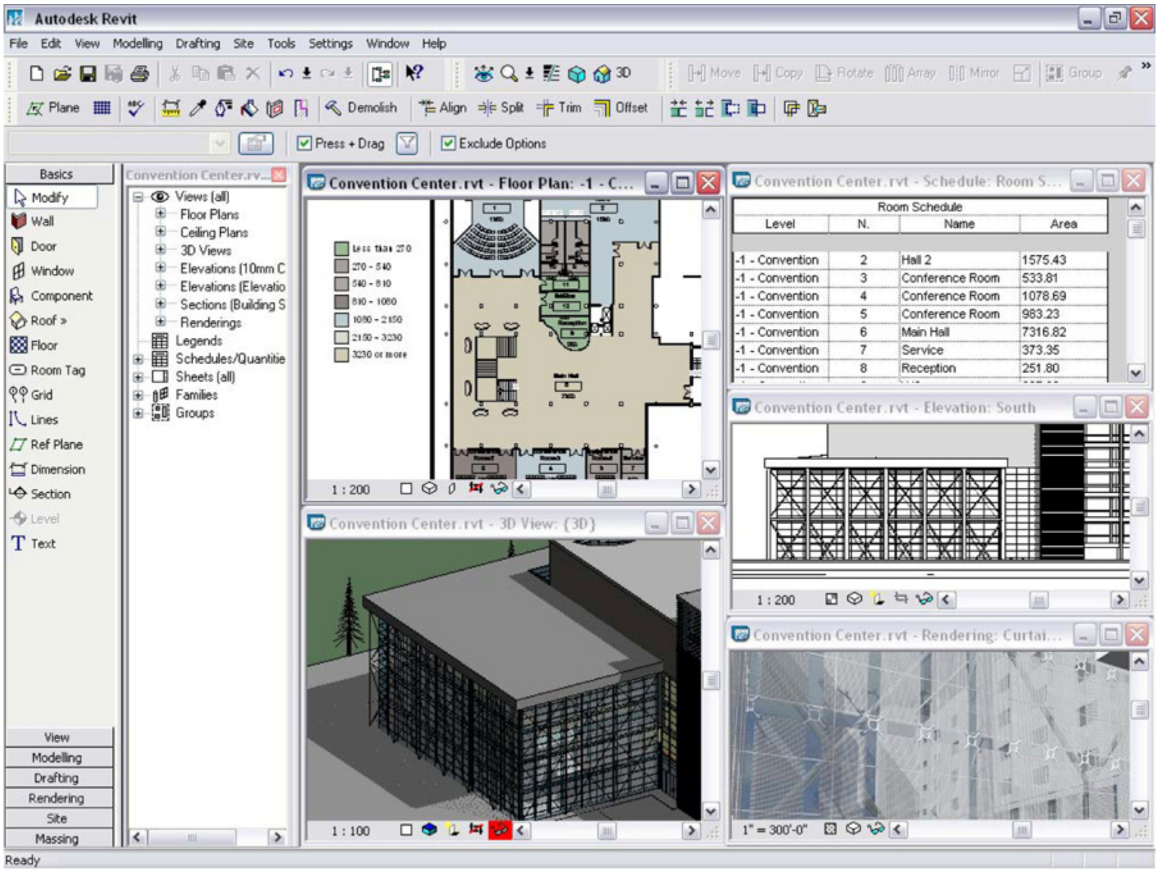

Figure 4.4. Screenshot of Autodesk Revit BIM Software

One of the current limitations with BIM software is that it is clearly oriented towards normative and common building types[70]. Many of the objects and components within these programs are defined by the vendors and they are largely represented by common building parts found in the construction industry. Thus if an architect attempted to use non-standard components, they would either have to develop the components themselves or pursue alternative options. Also, the 3-D modeling capabilities of most

[70] Schodek, 123.

current BIM software systems is limited, meaning that complex forms and geometries are often difficult or impossible to model. BIM systems are currently geared towards allowing architects to model buildings from standard off-the-shelf components. Other 3-D parametric modeling programs impose fewer restrictions and are more flexible because they are used in many other industries. However, the additional freedom makes these programs unnecessarily complex for most of the tasks an architect would need to complete and they also may lack specific tools architects tend to use like generating drawing sheets and materials lists.

BIM software systems allow architects involved in prefabrication to better integrate the design and construction processes necessary to pull off a successful project. They allow all the involved professions to access a central model that the fabrication and assembly process will be derived from. As BIM software continues to develop, it will give architects even more control and flexibility to generate complex, high quality designs that can be easily broken down into simpler components for fabrication.

4.3. Computer-Aided Manufacturing (CAM) Technologies

Long used in modern industrial design and engineering, computer-aided manufacturing (CAM) technologies are starting to make their way into smaller scale, lower budget architectural design efforts, thanks to the rising awareness of prefabrication. While manufacturers of architectural hardware and building components regularly use CAM, architects themselves have not used it extensively to design and fabricate custom components and architectural elements. Therefore, unlike designers in other industries, they have been largely limited to the off-the-shelf building components that suppliers, vendors, and manufacturers can offer them. Now that CAM technologies are becoming more accessible through better software tools and lower costs, architects now have more freedom to design and fabricate their own architectural components. This increased control over design through technology is one of the key talking points behind the new movement in prefabrication.

Using off-the-shelf standardized components has been a recurring mantra of prefabrication in the past, since it relies on the manufacturers to factory-build many of the parts before they reach the site. The alternative, which architects like Gropius and Wachsmann attempted to do, was to develop a custom modular system of components to be used throughout the building. In this custom system, similar components like panels would be produced over and over and then pieced together as walls, floors, or roofs to generate the final plan and form of the house. Both cases are dependent on mass production to be economically viable. However, the problem with mass production in the building industry is the erratic nature of the ordering process[71]. This means that even if a large group of designers and builders agreed to purchase the same standardized components from a manufacturer, there is no guarantee that their demand will be spread out evenly across time and there might be periods of low and high orders. The principles and savings of mass production are broken if the manufacture cannot balance a steady input of orders with a steady output of production.

Mass production next evolved into the principle of lean production in the mid-1950s, when Taiichi Ohno, a production engineer at Toyota, began to look at ways to reduce waste in both materials and in the human time and effort being spent in the factories[72]. Rather than maximize factory production at all times, which would lead to stockpiling if

[71] Davies, 141.
[72] Davies, 142.

the demand was low, Ohno retooled the production line to be able to flexibly respond to orders in a just-in-time process. The efficiencies introduced by retraining how the employees worked helped to cut production costs and also allowed factory production to be able to handle lower volume orders.

The ability to execute the concept of mass customization is one of the primary strengths of CAM production. CAM technology is the invention of software tools and machinery that allow computer-based models, drawings, and representations to accurately control machines that physically manipulate materials. With this technology, standardization is no longer needed, as a "computer-controlled machine can make a hundred different components in almost the same time that it takes to make a hundred identical ones[73]." CAM technology combined with lean production has opened the door for the modern prefabricated building to be developed. The modern prefabricated building does not depend on standardization or traditional mass production; it is both custom-made and mass produced just-in-time. Prefabrication will no longer conjure up images of a monotonous, repeated design. With this technology, consumers will be able to purchase and configure a high-quality semi-unique house as if they were working with a traditional architect, but with the savings afforded by prefabrication. Mass customization can be approached in several different ways so it will be useful to identify some of the approaches that have been used in other industries to allow for customization on a mass-market scale before exploring how CAM is being used in architecture[74].

[73] Davies, 144.
[74] Shodek, 156.

- Component Sharing – Products share the same shape and are made from the same components but the color, pattern, or material of the components may be varied. This results in several different variations of the same product.

- Component Swapping – The appearance of each product is identical, but the internal components may vary. In this case performance and function are being customized.

- Cut-To-Fit – Generally for 2-D or extruded products, this variation depends on the size or length of the product needed. Materials are produced identically and then cut to size to depending on its function.

- Mixing – Product variation is achieved by selecting from a variety of components and mixing or assembling them together to produce several different completed products.

- Platform – The internal frame of the product is the same for each product but the shell is varied. This allows one type of functionality to be rebranded several different ways.

- Sectional – A common interface is developed and then a variety of shapes and colors are produced with this interface. Each of these acts as a building block which can connect to blocks at the common interface.

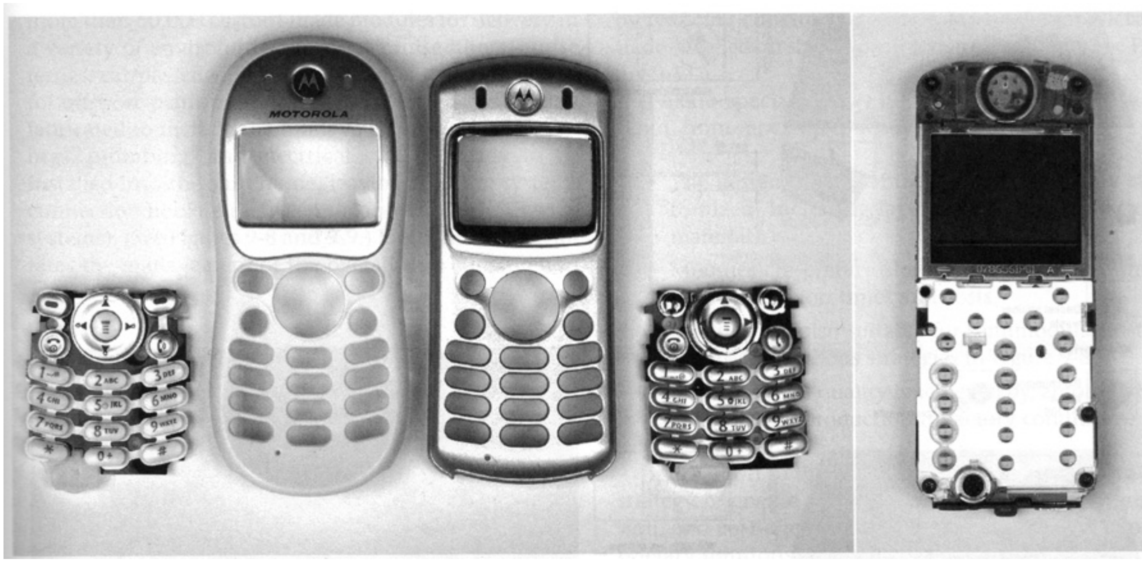

Figure 4.5. Example of Platform Modularity Based Mass Customization in Mobile Phones

Where these categories of modularity would not have been economically viable to produce in the past, CAM has now helped mass customization become a standard in industrial design. It is easy to see how these methods of customization can be applied to the architectural setting to help clients get the building customization they desire without having to pay a huge premium on design.

Computer-aided manufacturing works together with computer-aided design (CAD) tools and the computer controlled machinery to form the digital design and manufacturing environment. These three main components are defined as follows[75]:

- CAD System – A digital interactive design and analysis environment for making digital geometric models of the object to be eventually produced. Common CAD software used for CAM include CATIA, SolidWorks, and Unigraphics.

[75] Schodek, 4.

- CAM Software – Computer-aided manufacturing software wherein the user specifies how the digital design model is to be actually manufactured and creates a series of digital instructions for controlling specific machines. Typically the software will take the digital model created in the CAD system as input and output specific instructions for the machine which is to produce the object.

- CNC Machines – Computer numerically controlled (CNC) machines and related tools that translate these digital instructions into actual machine operations that make the object. Machines include CNC milling machines, routers, lathes, drills, saws, laser cutters, water jets, electric discharge machines, welders, and more. These machines either fabricate the objects directly or create negative molds for casing or injection molding.

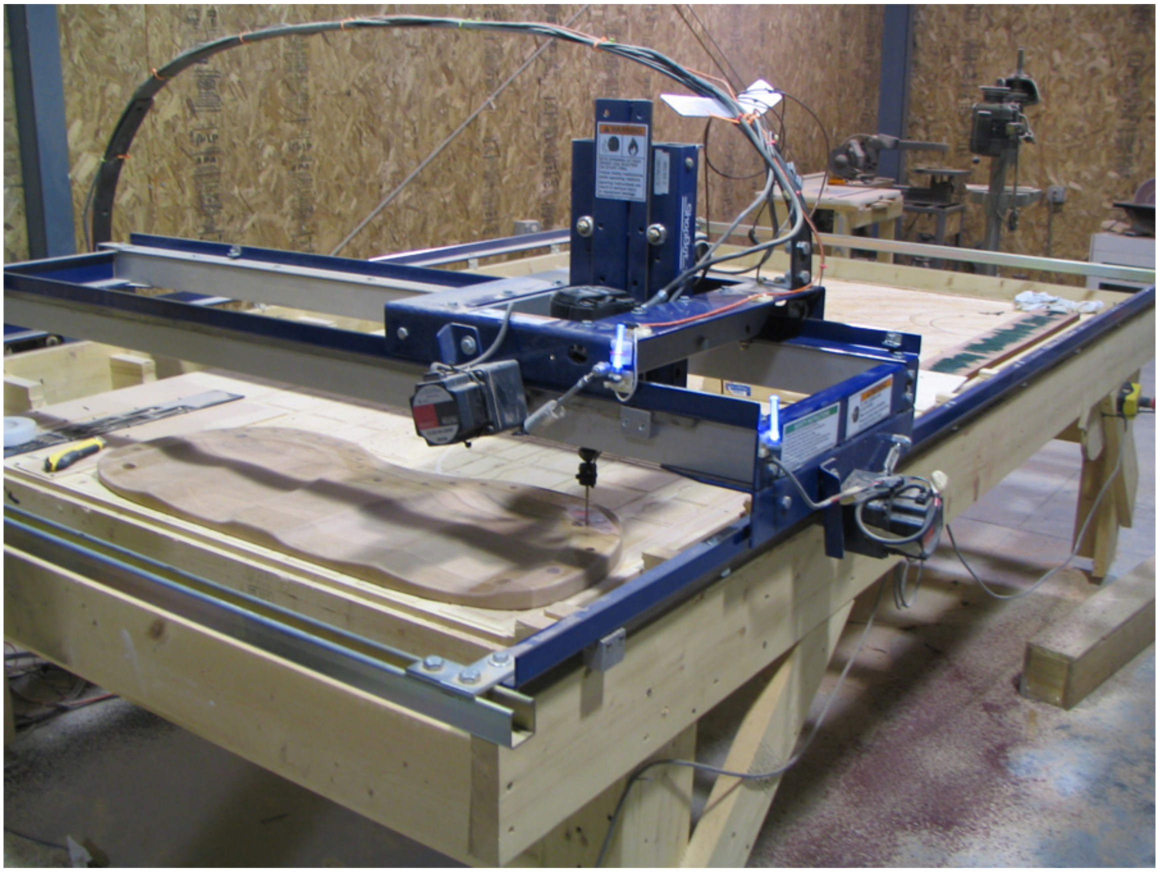

Figure 4.6. 3-Axis CNC Milling Machine

Designers have a large selection of CAD tools to choose from to draw, model and represent what they hope to fabricate. These tools can range from simple 2-D drawing programs to complex 3-D modelers, depending on the designer's intent and needs. However, it is important to realize that only certain methods of 3-D representation can be directly used in the CAM environment, so that selecting the appropriate software tools is essential[76]. Where many of the 3-D modeling tools used in practice by architects today are geared towards conceptual and schematic design activities, the CAM environment requires tools geared towards design development activities. In other words, software appropriate for the CAM environment is typically very complex and less intuitive to use

[76] Schodek, 5.

due to the high level of design detail needed to support the actual manufacturing of objects by computer controlled machinery. 3-D modeling representations usually fall into three categories: wireframe models, surface models, and solid models[77]. Wireframe and surface models are both excellent ways to visualize how and object might look, but they often don't contain the geometric precision and definition of mass that solid models provide. Thus, while some CAM systems do support surface models, solid models often provide the most accurate representation of a 3-D object to be fabricated.

In architecture, the use of CAD/CAM systems has been rising over the past few years, especially among larger profile architects who have been exploring free form shapes that cannot be fabricated conventionally. Some examples of famous architects that are highly engaged in digital design and fabrication include Frank Gehry, Bernhard Franken, Peter Cook, and Norman Foster. The projects they work on have usually been large enough to justify the custom fabrication of architectural components or are given a large budget for creative purposes. Only more recently have smaller projects with lower budgets been able to take advantage of CAD/CAM prefabrication, like Steven Holl's Turbulence House, Bill Massie's Big Belt House, and Bell Travers Willson's Digital House. With the help of CAD/CAM systems, many young emerging architecture firms taking on a more hands-on workshop approach that allows them to design innovative structures that are built in non-conventional ways. In academia, architecture schools are offering more courses and equipment to educate students about the possibilities of these technologies in architecture. As upcoming architects begin to learn how to use computer-aided design and manufacturing, there will be a higher demand for the

[77] Schodek, 6.

software and hardware, which will allow smaller firms to either operate their own fabrication labs or to outsource the fabrication at a lower cost.

Figure 4.7. BMW Dynaform Exhibition Space by Bernhard Franken

When designing in a digital environment with the intention of also fabricating through CNC machinery, architects usually take one of two approaches. Some architects begin designing on paper, with the intention of later bringing in their design to the CAD environment. Other architects begin in the CAD environment and use the computer to generate forms and shapes that would have been difficult to create by hand. In the first case, when bringing the design into CAD for CAM, the primary goal is to structurally rationalize their design so that it is constructible. For example, if they are attempting to design a building with complex curved surfaces, they will have to rationalize the structural system to be used and how the curved enclosure will be subdivided for fabrication. In the second case, the architect uses the CAD software as a method of digital form-finding. For example, they might either use a program's tools to generate forms or they might input mathematical formulas into the program to generate forms and then parametrically vary dimensions to refine the form. There are many other ways architects utilize CAD and CAM tools for design, but these approaches illustrate how the field is encouraging innovation that will add unique qualities to buildings designed and constructed using these methods.

The adoption of CAD / CAM technologies in conjunction with the methodologies of mass customization will be essential for architects to design and build high-quality innovative buildings at a reasonable and competitive price. These are both modern technologies and ideas that have been successfully introduced in other industries and it is logical and relatively simple to transfer them into the architecture and construction industry. Whereas old concepts like mass production were difficult to actually implement into architecture prefabrication, these modern concepts fit perfectly into a field that has lower production volumes but also highly values uniqueness and customization. Traditional cost-saving advantages of factory construction are achieved as well as new advantages such as highly precise construction and innovative design possibilities. It is important that architects use these modern prefabrication technologies to their benefit, as it will help them produce high-value architecture that can better compete with the current low-cost, minimally designed structures that are prevalent throughout the world today.

5. Design Prototype: Putting it All Together

Having explored the housing market in Oahu, prefabricated housing efforts in the past, present, and future, and the key technologies driving modern prefabrication, a critical analysis is necessary to determine what the proper approach to developing prefabricated housing in Oahu should be. Three factors to assess in this context include:

- What type of housing is most appropriate and needed for the future development of Oahu? Where should this housing be located?

- What are the design criteria that should be used to access the quality of housing? What are the factors that need to be considered in developing a high-performance home in Oahu?

- How does modern prefabrication help meet the prescribed design criteria? What are the appropriate materials and prefabrication methods to use in the context of Oahu?

Once these factors have been analyzed, a comprehensive design prototype will be proposed to illustrate how prefabricated housing might be effectively deployed in Oahu.

5.1. Developing Multi-Family Housing in Oahu

As the issue of affordable housing in Oahu continues to grow, both developers and homebuyers need to look beyond traditional solutions to find a fresh approach that addresses the changing needs of the future. The housing market in Oahu is subject to different forces that don't always apply in other markets in the United States. While other markets are beginning to see decreases in median home sales prices after a strong five year run, median prices in Oahu are continuing to increase, albeit at a slower pace. Reasons include the limited amount of land available for private development, speculative buying from non-local investors, the rising costs of construction, and developers building larger homes to increase profits. Even though median home prices are increasing at a faster pace than median incomes and further exacerbating the problem, it is difficult to see where the breaking point is when prices will begin to fall. Because developers are still selling homes at market prices, there is no urgency to change what they are doing. For the most part they seem to be focusing on building large suburban developments of single-family homes in West Oahu, which are inherently more expensive due to the amount of land and material needed, rather than looking at better ways to redevelop urban neighborhoods and reduce sprawl.

Given the growing population density, commuting and traffic problems, and negative environmental impact of sprawl, it makes sense to turn to the development of multi-family housing to create better living environments. However, there needs to be a better vision and strategy in developing multi-family housing, rather than continuing to build impersonal high-rise condominiums and unimaginative low-rise concrete apartment buildings in residential-only zoned neighborhoods. Future multi-family housing projects in Oahu should be developed in the context of mixed-use neighborhoods for financial, social, and environmental reasons. Not only may these mixed-use units cost less for the homebuyer, but the surrounding neighborhood will enjoy an improved quality of life and decreased pollution by promoting a more active, pedestrian-friendly, and public transit oriented environment. This model of mixed-use living has proved to be successful in other major cities around the world, and it is time for Oahu to implement it more extensively as a means to provide better quality housing at a lower costs.

In order for this to happen there first needs to be a fundamental shift in the type of housing that homebuyers in Oahu are demanding. Developers and the government will adapt accordingly if there is a growing demand for mixed-use zoning and development from the community. Thus it is the job of architects and planners to educate the community and encourage them to demand new models of mixed-use neighborhoods with a diverse palette of housing options. Otherwise, developers will simply continue to build as they have, further propagating car-dependant suburban communities in response to the demand for single-family homes. One obstacle to increasing this demand is the perceived higher status and value of owning single-family homes, which has long been the vision of homeownership in America. Granted there are disadvantages to urban living such as reduced privacy and less open space, the affordability, efficiency, and convenience of the urban model of living simply makes sense in Oahu where land for development has always been limited and the growing population is overstraining the current transportation infrastructure. Mixed use urban development is essential to the future long-term health of cities in Oahu, especially along the southern shore.

If multi-family housing is built independent of longer term mixed-use planning, it will fail to gain the critical mass appeal necessary for its success. It must be marketed to homebuyers as a change in lifestyle that is more attractive and value-laden than the typical suburban life. It should not be targeted at any particular income bracket, and instead provide an appropriate mix of options that range from affordable to luxury. Because of the perception that multi-family units are a lesser class of housing, the quality of the units should clearly exceed what the buyer could get with a single-family home of the same price. The criteria that determine quality will be discussed further in the following section.

The upcoming Honolulu High-Capacity Transit Corridor Project provides a perfect opportunity to begin pushing for mixed-use development. The government and local planners are taking the right steps by promoting and offering transit-oriented development community meetings. New neighborhood dynamics will naturally form around the transit nodes, so it is important that these areas are re-zoned and re-developed to accommodate these changes. Transit ridership will bring new business to these nodes, giving them the opportunity to be convenient areas to live and work. Mixed-use development with office, commercial, and residential buildings will help provide this type of environment and begin to attract a greater demand for housing in these urban neighborhoods.

While it is easy to imagine that zoning densities can be increased so that urban housing solutions become viable, the reality is that there are many other complex issues that need to be addressed for this to happen, many outside the scope of this project. There are larger issues of urban planning and massing that need to be studied to determine the suitability and placement of high density mixed-use neighborhoods. A primary concern is the ability for the current utility and transportation infrastructure to handle increased densities. Urban infill sites would be equipped for these changes but rezoning previously low density, single-function areas might require extensive infrastructure upgrades, which would be costly and time-consuming. Because the higher density would likely mean increased height limits and more residents, there would undoubtedly be neighbor concerns about noise, traffic, blocked views and daylight, crime, and pollution. There must be a longer term strategy in place for how the mixed-use community will be incrementally developed and how it will integrate with the surrounding areas. Sustainability issues within the proposed community, both environmental and economic, will need to be addressed to ensure the neighborhood grows and succeeds.

Although the above considerations will not be addressed in the design prototype proposed in this project, they are recognized as important factors that must be resolved before anything can be realistically designed and built. Therefore, while a building's connection to the ground and its relationship to the site are of the utmost importance, this housing prototype will aim to be flexible enough to adapt to a variety of appropriate zoning conditions in the City and County of Honolulu Land Use Ordinance (LUO). The LUO provides guidelines for minimum lot dimensions, setbacks, site coverage, height limits, maximum densities, and more. It is recognized that selecting generic Oahu sites cannot take into account important site characteristics such as grading issues, soil conditions, infrastructure, neighboring buildings and services, existing community amenities. However, there are still many conditions general to sites in Oahu that will play a significant role in the design. These include environmental factors such as climate, sun angles, and trade winds. The design prototype will make several assumptions that stay within the confines of reality, while simultaneously generating ideas and discussion on the application of modern prefabrication technologies to the design and construction process.

The goal of the design prototype is to propose a flexible multi-family housing solution in a mid-to-high density urban mixed-use neighborhood in Oahu. Housing nearly one-third of Oahu's population, Honolulu would be the ideal location with the population density to support the design prototype. In addition to providing both residential and commercial uses, some important characteristics implied by an urban mixed-use neighborhood include the availability of public transportation, pedestrian and bike oriented planning and services, shared public open spaces and community facilities, and parking support. Details of mixed-use planning will not be covered but the design prototype is envisioned to be a flexible piece that can be plugged into sites within this type of environment. The housing component of a mixed-use neighborhood can include a range of types, sizes, and affordability, depending on the planned residential population. For mid-density developments, the ideal building might have commercial retail spaces at the ground floor street level with townhouses or mid-rise apartments above. For high-density developments, the first few floors may include commercial retail spaces, and the upper floors of the high-rise can be a mix of office space and condominiums. Based on this general vision of a residential mixed-use building in mid-density neighborhoods, this project aims to design a flexible and expandable housing prototype system that uses a townhouse model as the minimum base unit.

As defined by the Urban Land Institute, a townhouse refers to "the physical form of two or more single-family attached homes with a ground floor entry[78]." Ownership of the townhouse is similar to ownership of a single-family home, with a community association usually holding the title to any common property. While historically townhouses have been prevalent in the form of row houses on single lots in urban cities, they also have

[78] Robert E. Engstrom and Marc R. Putman, *Planning and Design of Townhouses and Condominiums* (Washington D.C.: The Urban Land Institute, 1979), 2.

taken the form of suburban community developments. Regardless of its setting, it offers the advantages of energy efficiency, efficient construction and land development costs, land conservation, lower public maintenance and energy costs, better security and community, and a lower maintenance lifestyle[79]. With its own street-level entry, the townhouse can provide the urban dweller the feel and privacy of a single-family home, which is often lost in larger city apartment buildings with a single shared lobby entrance. At the same time, the townhouse owner can take advantage of all the conveniences that density affords.

Relative to design, the character of the townhouse is essentially defined by its limitations. Architect Alexander Gorlin attempts to describe this:

> "The town house is one of the basic building blocks of the city. Defined by two parallel walls and vertically oriented circulation, it is commonly three to five stories tall, the maximum comfortable climb by a person… The town house is both an individual actor on the stage of the street and also a replicable unit that can be combined to make urban configurations that extend the plan of the city… The town house is a typology of enormous restrictions, and therefore a laboratory of creative possibilities within a very limited realm. The parallel walls that define the town house type were established by certain structural and economic considerations that allow only a few options regarding circulation, floor area, entry, and functional organization[80]."

In addition to the challenges of size and circulation due to the small footprint of the townhouse, shared walls between units often limit the open façades to a front and a back. This limits design opportunities for natural lighting and ventilation and requires that these two facades be carefully analyzed.

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[79] Ibid., 6.

[80] Alexander Gorlin, *The New American Town House* (New York.: Rizzoli International Publications, Inc., 1999), 10.

Figure 5.1. New York Townhouses in Urban Infill Sites by Tod Williams Billie Tsien Architects (left) and Ogawa Depardon Architects (right)

To better establish how the townhouse can fit into the urban fabric of Oahu, the appropriate existing zoning laws must be first examined. The two appropriate types of zoning for mixed-use residential development are Apartment Mixed Use Districts (AMX) and Business Mixed Use Districts (BMX). The LUO describes the purpose and intent of these districts as the following:

> "The purpose of the apartment mixed use districts is to allow some commercial uses in apartment neighborhoods. The additional commercial uses shall be permitted under varying intensities and are intended to support the daily and weekly commercial service needs of the neighborhood, conserve transportation energy by lessening automobile dependency, create more diverse neighborhoods and optimize the use of both land and available urban services and facilities. Mixing may occur horizontally and vertically, but controls are established to maintain the character of these neighborhoods primarily as apartment neighborhoods[81]."

> "The purpose of the business mixed use districts is to recognize that certain areas of the city have historically been mixtures of commercial and residential uses, occurring vertically and horizontally and to encourage the continuance and strengthening of this pattern. It is the intent to provide residences in very close proximity to employment and retail opportunities, provide innovative and stimulating living environments and reduce overall neighborhood energy consumption[82]."

Based on these descriptions, it is apparent that BMX districts have more flexibility in creating a more diverse mix of uses, since AMX applies restrictions to the amount of non-residential uses allowed. Because, the design should be flexible enough to be developed in any of these zoning districts, the minimum configuration of the prototype will attempt to meet the most restrictive requirements. The following table of information from the LUO displays mixed-use development standards for the AMX and BMX mid-to-high density parcels that will be designed for:

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[81] Department of Planning and Permitting, *Land Use Ordinance* (Honolulu: City and County of Honolulu, 2003), 52.
[82] Ibid., 57.

Table 5.1. City and County of Honolulu Land Use Ordinance Development Standards for Apartment Mixed Use and Business Mixed Use Districts

Development Standards	District		
	AMX-2	**AMX-3**	**BMX-3**
Minimum Lot Area	10,000 sqft.	15,000 sqft.	5,000 sqft.
Minimum Lot Width and Depth	70 ft.	70 ft.	50 ft.
Front Yard	10 ft.	10 ft.	10 ft.
Side and Rear Yards	**Use Type** Duplex Lots Detached (1 – 2 Units) Multi-family (3+ Units)	**Requirement** 0 ft. for common walls, 5 ft. elsewhere 5 ft. 10 ft.	
Maximum Commercial Use Density (FAR)	FAR=0.4	FAR=0.6	N/A
Maximum Building Area	**Lot Area** 10,000 – 20,000 sqft. Over 20,000 sqft.	**Requirement** 50% of zoning lot 40% of zoning lot	Not Regulated
Maximum Height	Per Zoning Map. In Honolulu, AMX-2, AMX-3, and BMX-3 parcels typically have a maximum heights ranging from 60 to 150 feet.		
Height Setbacks	For any portion of the structure over 40 feet in height, additional side and rear setbacks shall be provided; for each 10 feet of additional height or portion thereof, an additional one-foot setback shall be provided. The additional setback shall be a continuous plane from the top of the structure to the height of 40 feet above grade.		No portion of a structure shall exceed a height equal to 2x the distance from the structure to the vertical projection of the center line of any street.
Maximum Density (FAR) for AMX-2	**Lot Area** 10,000 – 40,000 sqft. Over 40,000 sqft.	**FAR Calculation** FAR=(.00009 x lot area)+0.4 FAR=1.9	
Maximum Density (FAR) for AMX-3	**Lot Area** 10,000 – 20,000 sqft. 20,000 – 40,000 sqft. Over 40,000 sqft.	**FAR Calculation** FAR=(.00004 x lot area)+1.6 FAR=(.00002 x lot area)+2.0 FAR=2.8	
Maximum Density (FAR) for BMX-3			FAR=2.5

Open Space Bonus for BMX-3	For each square foot of public open space provided, five square feet of floor area may be added, exclusive of required yards; For each square foot of arcade area provided, three square feet of floor area may be added, exclusive of required yards; and Maximum density with open space bonuses shall not exceed an FAR of 3.5.	
Off-Street Parking Requirements	**Use** General Business Food / Grocery Stores Eating & Drinking Duplex Dwellings Multi-family Dwellings	**Requirement** 1 per 400 sqft. 1 per 300 sqft. 1 per 400 sqft. 2 per unit plus 1 per 1,000 sqft. over 2,500 sqft. 2 per unit > 800 sqft. + 1 guest stall per 10 units
Loading Requirements	Multi-family Dwellings Business and Retail	1 per 20 – 150 Units 2 per 151 – 300 Units 1 per 2,000 – 10,000 sqft. 2 per 10,001 – 20,000 sqft

Given the above development standards, the design prototype will initially explore townhouse configurations that meet the minimum requirements for both AMX and BMX zoning districts. Having met these conditions, larger developments may also be proposed. Whether developed in a larger community block context or as a few units in an infill site, the townhouse will be an important residential typology in the creation of urban mixed-use communities in Oahu. An attractive alternative to the typical apartment or condominium building, townhouses can combine the advantages of density with the desire for privacy and individuality in an urban dwelling. Therefore, multi-family development of townhouses can be an exciting and highly marketable solution to developing high-quality urban housing in Oahu.

5.2. Raising the Standard of Quality in Oahu Housing

As one explores the various neighborhoods in Oahu, there are few homes that broadcast a high level of quality and performance. Most multi-family units like high-rise condominiums and mid-rise or low-rise apartments are even less original, further supporting the idea that they are less ideal than single-family homes. Cost plays a large role in this general lack of quality housing. But if it can be shown that higher quality can be achieved at the same or lower costs, there is no reason why the quality of housing in Oahu cannot be significantly increased. Before proposing how this can be done, it is necessary to define the criteria that determine what quality in housing means in the context of Oahu. Quality is a broad term that cannot be singularly defined by any of the various factors of design. Design goes beyond form, space, and order and into issues of environmental impact, energy and water efficiency, material selection, occupant comfort, aesthetics, and overall cost and value. A high-quality house is able to find a balance between all these design forces that are often pulling strongly in different directions, resulting in home that is satisfying to the owner, builder, and designer. While the issues facing the architect and contractor during the design and construction of a home define the goals of quality design, nothing is validated until the eventual occupant can objectively and subjectively affirm that the original design intentions hold true.

With rising energy costs and growing concern over the destruction of the environment, it is not surprising that sustainable design has become the primary measurable benchmark for specifying a high-quality building. Blessed with a comfortable year-round climate that produces a lush tropical environment, Hawaii residents are particularly proud and vocal when it comes to preserving their environment. Therefore it is imperative that all buildings in Hawaii work together with the climate and land to provide comfortable indoor and outdoor environments without relying on traditional sources of energy. With a climate where heating is generally not a factor, this largely means reducing or eliminating the need for air conditioning, one of the most significant energy loads in a Hawaiian home. In addition to reducing the need for air conditioning to provide thermal comfort, strategies should be implemented to save energy needed to provide lighting, hot water, and additional electrical needs.

Where the above are the environmental and energy issues that directly affect the end-user of a home, sustainability is an all encompassing design concept that needs to be thoroughly judged from what Architect William McDonough describes as “Cradle to Cradle.” There should be no “end” product of a home with a perceived lifespan, and instead designers need to design with a continuous lifecycle in mind. This means that ideally the materials and construction process of a building are born out of the reuse, recycling, or reprocessing of previous materials. Therefore, when dismantled, the building components can be further reused, recycled, or reprocessed to build another building or take on another function. While wholly embodying the “Cradle to Cradle” concept may be difficult, there is no doubt that the general construction process and material selection can be made more efficient and sustainable and that building products can be designed for future reuse. Prefabrication fits well into this concept.

There are many different strategies that can be utilized to effectively design a high-quality sustainable urban townhouse prototype for Oahu. However, to more effectively define quality and to be able to compare two different buildings, there should be a set of recognized quantitative benchmarks that all sustainable buildings strive to achieve. The United States Green Building Council (USGBC) set out to produce this set of standard benchmarks with their Leadership in Energy and Environmental Design (LEED) building rating system program. While the LEED rating system is largely prescriptive with a largely non-weighted point system that awards points based on process implementation and meeting percentage threshold requirements, it nonetheless provides clear guidelines on which architects can develop and judge their designs. Regardless of whether the developer of a building actually pursues LEED accreditation, the rating system can be used as an effective reference for designing sustainable buildings. For the purposes of the prototype townhouse to be investigated, a specific rating level will not be pursued but the various LEED credits will be used as a benchmark to achieve specific sustainable design goals. Below, the main divisions of the most current LEED for Homes building rating system will be reviewed and strategies to achieve certain benchmarks will be briefly outlined, particularly those that should not add any significant cost to the construction.

The Location and Linkages division of LEED for Homes looks at how site selection and surrounding infrastructure can reduce the environmental impact of the home. Preference is given to building on previously developed lots that are served by or located near existing infrastructure. Site planning that encourages walking, biking, or public transportation is highly encouraged.

Because the goal of the prototype is to promote housing development in urban sites, many of the site selection preferences will be met. Properties in urban areas are typically infill sites that have been previously developed. They are also inherently part of an existing or planned density that offers existing sewer and water supply infrastructure and provides public transportation that can reduce the need for personal automobile use. Oahu's bus system already enjoys extensive coverage across the island and the addition of a mass transit system in the future will further encourage the development of pedestrian oriented communities. Mixed-use development provides close and accessible community resources, reducing the resident's dependency on personal automobiles to run errands. The vision of a townhouse located in a dense mixed-use neighborhood is very much in line with the sustainable strategies outlined in LEED's Location and Linkages division.

The Sustainable Sites division of LEED for Homes focuses on how proper site development can reduce construction impact on the environment. Before construction begins, a construction activity pollution prevention plan should be developed to reduce pollution from erosion, sedimentation, and airborne dust. Landscaping should be designed to avoid invasive plants and instead, native species should be planted to minimize the need for irrigation or fertilizer for the landscaping. Sustainable Sites also looks at how surface water is managed, how heat-island effect is reduced from site surfaces, and how non-toxic pest-control measures are implemented.

Although it will be an added cost to construction, the benefits of green vegetated roofs are significant. In a dense urban infill situation where there is not much room for open green space, an accessible green roof can provide a private escape from the city. Plants and vegetation placed on the roof of the townhouse will significantly reduce and control storm water runoff while also minimizing heat island effect. Native species will be selected so that little maintenance or watering is required to sustain the green roof. At the ground level, there will also be an attempt to provide as much natural landscaping as possible with native plants and trees and limited amounts of conventional turf. Permeable pavers will be used in place of typically impermeable surfaces like driveways and walkways to further deal with storm water runoff. Since very little wood will be used and most of the materials do not provide any nutrients to insects and animals, fewer pest control measures will need to be taken.

The Water Efficiency division targets three areas for improvement: water reuse, irrigation system, and indoor water use. Buildings should look to use municipal recycled water or to install systems that harvest rainwater or reuse graywater. There should be an attempt to reduce the use of potable water for landscape irrigation. Indoor water use reduction can be achieved in the fixtures specified and the implementation specific technologies such as storm water and graywater reuse for flushing or on-site wastewater treatment.

As mentioned above, the plants and vegetation specified for the site and roof will attempt to only use native species that do not need additional irrigation. Hawaii's tropical environment will usually provide enough moisture and rain to keep most native plants healthy. This should thus eliminate any water use for irrigation in the project. High-efficiency water fixtures and appliances will be specified throughout the prototype to reduce potable water use in both graywater and blackwater functions. The installation of rainwater harvesting or on-site wastewater treatment will depend on the size of the development. If there are enough townhouses built to allow for a larger shared system, then they will be implemented.

The Energy and Atmosphere division requires that the house meets or exceeds the minimum energy performance requirements based on the Energy Star for Homes standards. LEED points are achieved for performance beyond the Energy Star standard through the Home Energy Standards (HERS) Index, which rates a home's energy performance. The index provides a scale that ranges from an energy-efficient reference home to a net zero-energy home. This is one of the more open-ended categories in the

LEED system, as there are a wide variety of strategies that can be employed to reduce energy use and optimize energy performance.

Many of the design decisions to be made in the townhouse prototype will be geared at reducing the need for air-conditioning, artificial lighting, and water heating. Passive solar and ventilation strategies include orienting the building to minimize solar heat gain and to encourage natural ventilation from Oahu's northeasterly trade winds, providing overhangs and shading devices to eliminate direct sunlight from heating the house, installing effective insulation through wall material selection and radiant barriers, building vegetated green roofs, providing open floor plans and operable windows that encourage natural ventilation, and designing vertical openings that allow heat to rise through the house and be flushed out from the roof. The insulation on the roof is particularly important in Oahu where the sun is often directly overhead during the summer months. Active components which will be installed on the roof include solar hot water collectors and optional photovoltaic panels. Light colors will be specified in room finishes to enhance lighting. Where electric lighting is needed, energy efficient fluorescent or LED bulbs will be specified. Energy efficient appliances such as refrigerators, dishwashers, and clothes washers will also be specified. The goal for the townhouse is to implement as many measures possible to reduce dependency on electricity. During the design stage it will be important to run computer-based environmental analysis studies on the housing model to predict its performance and then make iterative improvements.

If air conditioning is required by the occupants, it is likely that units will be window based so that they are zone specific and easy to maintain from the lanais of the townhouse. Central air conditioning systems can also be placed on the roof if necessary. The units specified will use refrigerants that do not contribute to ozone depletion or global warming and will also be shaded as well as possible to increase performance efficiency. In the air conditioning state, the insulation of the building becomes very important for retaining the cool temperatures. A measurement and verification plan will be set in place to evaluate how the building actually performs.

The Materials and Resources division of LEED for Homes is an important measuring point for the prefabrication aspects of this project. While many of the framing requirements are specific to typical stud wall framing, there is recognition for prefabricated panelized or modular construction techniques in LEED's rating system. Environmentally preferable products are recommended, including certified wood, reused materials, materials with recycled content, regional materials, and rapidly renewable materials. Also, all adhesives, sealants, paints, coatings, carpets, composite wood, and agrifiber products need to emit minimum amounts of Volatile Organic Compounds (VOC) as specified by a wide range of industry standards. The reduction and management of construction waste is also an important consideration in this division.

Construction waste management is an important advantage of off-site prefabrication, as almost all of the primary components of the building are delivered to the site ready to be installed without any further on-site processing. Leftover materials from fabrication in the factory can be reused or recycled. The townhouse prototype should be able to easily divert on-site construction and land-clearing debris from disposal in landfills and incinerators. Hawaii's remote location will make it challenging to specify a large amount of regionally produced materials. Recycled and renewable materials will be used as much as possible. All steel and concrete will contain recycled content while exterior and interior non-structural wood components like shading devices will look to use bamboo, a rapidly renewable material. Wood will be used sparingly in the project since a wood structural system will not be specified, and where needed, wood-based products will be certified by the Forest Stewardship Council (FSC).

The Indoor Environmental Quality division of LEED for Homes focuses on occupant health and comfort by setting standards for material emissions, thermal comfort, daylighting, and systems controls. LEED requires that the building meets and exceeds the baseline requirements for indoor air quality (IAQ) as specified by the Energy Star with Indoor Air Package standard. Alternatively, points are achieved through a variety of prescriptive measures that take venting, outdoor air ventilation, exhaust, filtering, contaminant control and protection into account.

Part of the townhouse prototype design challenge is to develop a well ventilated and day lit space within a narrow building envelope that offers only two facades. Floor-to-ceiling window walls on these two facades with work together with overhangs, shading devices, and screens to allow plenty of indirect daylight into the townhouse. The installation of operable casement windows will allow the building to enjoy natural ventilation also let occupants directly control the amount of ventilation available. Additional skylights and clerestory windows will also be effectively implemented to provide more daylight and also allow heat to escape vertically from the house.

Further points in LEED are awarded in the Awareness and Education division and the Innovation and Design Process division. These divisions take into account any regional innovations in the design not accounted for by the other divisions, project planning steps taken by the design team, and any methods of training homeowners, tenants, and building managers on how to operate and maintain the building.

The above criterion specified by LEED provides a standard way to judge the quality and effectiveness of future housing construction in Oahu. Even if LEED is not used as a guideline for sustainable design, it is important to set benchmarks and goals regarding site development, energy performance, water-use, material selection, and indoor environmental quality. Most of these criteria can be attained at little or no additional cost through good design, sensible material and appliance choices, and intelligent construction methods. In addition to the LEED for Homes building rating system, an excellent resource for more information on the energy performance aspects of the home quality criteria can be found in the State of Hawaii's *Field Guide for Energy Performance, Comfort, and Value in Hawaii Homes* from the Department of Business, Economic Development & Tourism.

While sustainability provides a more objective and quantifiable standard for quality, there are also a few subjective measures when judging the quality of a house. Cultural site context and "livability" are two factors that cannot be measured but are more or less recognizable in a home's design. For cultural context, it is important to understand the lifestyle and activities of the surrounding culture, particularly if the house is a speculative building without the direct input of the eventual homeowners. In Oahu, much of the family lifestyle is adapted from Asian and Polynesian cultures, often making living arrangements different from the mainland or other countries. Several generations might live under the same roof and the house should be flexible enough to take this into account. Private outdoor spaces like lanais are also important given that the culture is very outdoors oriented.

Livability is an even more most subjective and wide-ranging criteria for quality. It takes into account the functionality, usability, and overall atmosphere of the house. Many issues come into play, but the first is whether the house fits the user's program or is flexible enough to adapt to different uses. This takes into account everything from room adjacencies and circulation through the unit to the way the kitchen is laid out and how accessible cabinets are. Efficient use of space and appropriate scaled rooms also play a role in the livability of a house. Too often houses are built with more space than is actually needed, resulting in an energy inefficient and impersonal unit. Privacy, both visual and sound, is particularly important in denser shared multi-family housing. Because of the year-round pleasant weather in Oahu, residents will often have their windows open for air circulation, which may lead to noise privacy issues. Along with addressing these privacy issues in multi-family buildings, sufficient shared public spaces and amenities must also be provided to offset the lack of private yards. A quality livable house is harmonious with the dwellers' needs and is also able to directly enhance their lifestyle.

These more subjective qualities will be largely addressed in the program, layout, and general design of the townhouse prototype. One goal will be to provide each room with accessible outdoor lanai spaces. Full height window walls shaded by overhangs and other devices combined with operable windows will attempt to blur the boundary between indoor and outdoor spaces to celebrate the year-round comfortable climate. Vertical openings and double height spaces will be employed to add a greater degree of spatial freedom and variation between floors. Given the narrow width of the townhouse, flexibility in spatial arrangement will be challenging. However, architectural elements such as double height spaces will help eliminate the narrow feel of the townhouse. All of these architectural design features will influence the perceived quality of the townhouse prototype so each must be considered carefully, especially in regard to their sustainable characteristics. Only through comprehensive analysis and evaluation of whole-building design concepts can the standard for any type of housing in Oahu can be raised to the next level.

5.3. Applying Prefabrication to Achieve "More for Less"

Now that a design criteria has been established for measuring the quality of housing, the case can be made that modern prefabrication technology can be utilized to help achieve several of these benchmarks at reasonable cost. The virtues of modern prefabrication for the designer and builder are clear: higher quality, precise, complexly shaped, mass customizable building components that can be fabricated faster and cheaper compared to the equivalent in conventional construction. The unique balance of standardization and customization inherent in the processes of modern prefabrication greatly benefit potential customers by lowering costs while still providing options for personalization. Future owners will be able to obtain relatively accurate cost estimates due to the standard pre-manufacturing of building components but will also be able to customize and configure the components without additional cost. In order for modern prefabrication to succeed, a comprehensive plan outlining the entire process must be designed and developed. Important issues that must be addressed by the plan include the supply chain, information exchange medium, material and fabrication costs, site delivery logistics, and on-site assembly steps. Only when all these issues have been resolved can prefabrication be taken from concept to reality.

Modern prefabrication relies on computer technology to rationalize the design of complex forms, produce parametric variations, generate cutting instructions for components, visualize the assembly process of part and whole, and organize materials and building information. In doing all these activities, the computer becomes the most important tool for information exchange among the various parties involved. The architect's role is to manage and simplify the format in which design information is shared throughout the project. This starts at the very beginning of a project, when software tools and information exchange processes are selected. BIM software is geared towards accomplishing the bulk of these tasks by providing tools to maintain an extensive real-time database of building components and their relationships to each other.

Early design work can be conducted in a variety of mediums, but once the building is ready to be modeled for fabrication, it is important to begin developing it in a BIM program. Potential fabricators and suppliers should be consulted early on to determine whether they can work with the BIM format chosen or if the format can be exported to one that they can use. For example, if the design model is developed in Autodesk Revit but the fabricator is only familiar with models developed in McNeel Rhinoceros or Dassault SolidWorks, it is up to the architect to either educate the fabricator on how to work with Revit models or to determine a way to export the model and associated building information to the other format. Ideally, all parties involved in the prefabrication process use the same BIM software format so that information can be exchanged in real-time with minimal difficulty.

In their prefabricated Loblolly house project, KieranTimberlake successfully implemented this approach to design information exchange. Within their Revit model, they stored detailed information about every building component including its dimensions, materials, part suppliers, and fabricator. Given this information provided within the Revit model, the suppliers and fabricators were able to precisely build the components off-site without needing to generate their own shop drawings.

For the development of the Oahu townhouse prototype, a combination of software tools will be used. Revit will be used as the primary BIM database storing all basic project information. Emulating the approach taken by KieranTimberlake, the software will be used to store relevant material and fabrication details in addition to the basic drawing and modeling of the building. For detailed development of building components, Dassault SolidWorks will be used. SolidWorks will provide more assembly oriented software tools where the prefabricated components can be broken down into individually designed elements. Furthermore, the parametric modeling capabilities of SolidWorks will be fully utilized to assist in the rationalization and simplification of components for fabrication. Components like floors and wall panels will be dimensionally driven so that many variations of the components can be created based on the same internal logic. The intention is that the development parametric design components will help fabricators easily build several custom components without incurring a large setup expense each time, the primary concept in of mass customization. Forms and patterns can be easily modified for reuse based on the parametric variability, meaning that hundreds of unique components can be derived from only a few base models. For the architect, these parametric components that are developed serve as the primary structural building blocks for the design of several different housing configurations and variations.

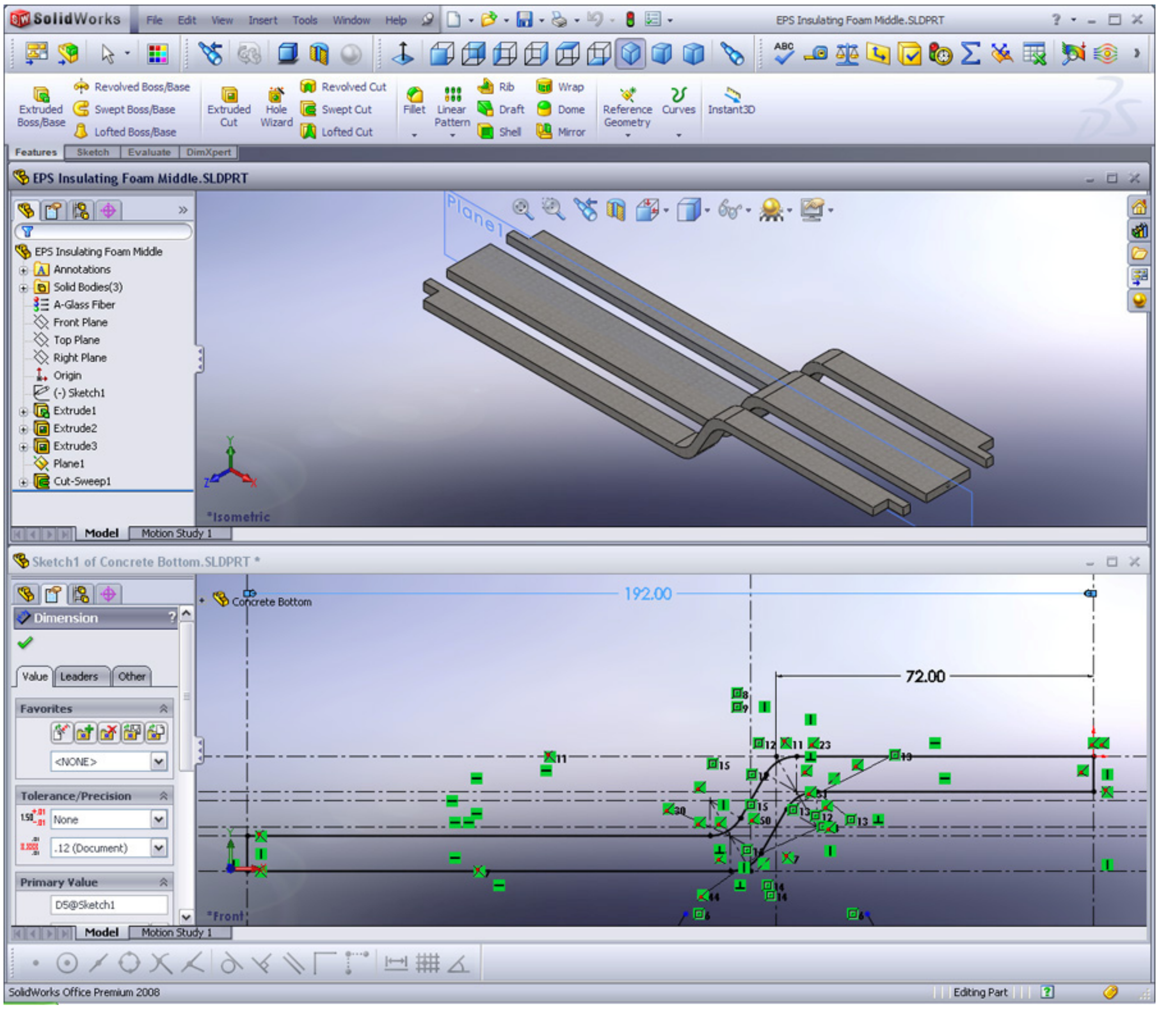


Figure 5.2. **Screenshot of Parametric Development Environment in Dassault SolidWorks**

Having digitally modeled the building components through BIM and other modeling software, fabricators will be able to directly convert the computer models to CNC cutting and milling code, simplifying a previously complex process and ensuring precision and consistency among parts. Although this opens the door for the creation of highly complex forms, the townhouse prototype will not strive to generate excessively complex shapes for the main structural elements, instead focusing on the standardization of a few non-typical forms that can be parametrically varied. For these structural elements, the goal is to strike a balance between reality and theory that leverages existing methods of building component fabrication and the digital fabrication of highly customizable and complex forms. On the other hand, interior non-structural and architectural elements can be easily developed with more creative forms with less material and structural analysis required. All elements are mass customizable to a certain extent, allowing potential homeowners to select from a set of customized configurations and building element variations.

The method of CNC digital fabrication used will depend on the materials being explored for the project. Wood products can be easily cut and shaped via CNC milling machines whereas metal and steel products would require laser cutting or water jet cutting tools. Concrete is more unique in that casting forms are milled out of foam blocks or insulating foam is milled to shapes where concrete is sprayed on. In both cases, the casting of the concrete can be completed either in a factory or on-site.

The establishment of a comprehensive BIM model and information exchange system will allow for the development of a supply and fabrication chain plan for the offsite construction of building components. This is perhaps the key challenge in implementing modern prefabrication efforts, as partnerships must be formed with investors, suppliers, and fabricators who are willing to embrace the technologies and goals involved in the prefabrication process. There are a variety of methods in which the supply chain can be setup depending on existing local resources, the types of materials to be used, the complexity of the component fabrication, and the scale of the project. If the project is a small scale structure using simple materials such as dimensional lumber or plywood, it is possible for the architect to act as the fabricator. In this case, materials would be obtained from a supplier and then directly cut and milled by the architect or by an outsourced fabricator at a shop with CNC cutting milling machines. This technology which some have called "file-to-factory"[83] should be readily available as CNC machines are widely used in engineering and shop-based industries. Several design-build architectural firms own their own CNC equipment and are able to prototype and fabricate many building components themselves.

At larger scales and for more complex components or assemblies, it makes sense to partner with a team of one or more fabricators that are responsible for the acquisition, processing, and sub-assembly of components. The fabricators will have better access to the tools and materials needed and also should have the experience to carry out production at larger scales. If the component assembly is not typical, it is important to form an early partnership so that feedback can be obtained during the initial design phases. The BIM model is an important tool to communicate how the component is designed and also how it will fit into the overall building.

Looking ahead, once the supply chain has been planned out, the shipping and assembly processes need to be examined. The size and finish level of the individual prefabricated components is important to consider. For some projects, the prefabricated units will be large room-size modules that will need to be shipped over roads and highways. Transportation and site accessibility become important in this case, as it will be difficult

[83] Branko Kolarevic, "Digital Fabrication: From Digital to Material," *Illinois Institute of Technology Arch 497 Website*, http://www.iit.edu/~mcleish/arch497_DDF/branko_kolarevic.pdf (accessed March 9, 2008).

to ship if there are not clear access roads for the trucks to deliver the modules. Instead of shipping large assembled components, an alternative solution would be to ship smaller components that require more assembly once on site. While one of the goals of prefabrication is to minimize the amount of on-site labor, assembly logistics often need to take precedence. On-site assembly information will be embedded within the BIM database, which will help identify where components are to be placed, how they are assembled and connected, and at what stage it is added to the overall building. The database will serve as a tracking device to identify various components on site and to determine where they belong in the final building assembly.

Because of all the information stored in the BIM model, upon completion of the building, the information in the model can be converted into a training and instruction manual for the owner. This can be done in a paper-based format or converted to a user-based electronic format[84]. Thus if a component in the building needs to be replaced, all the necessary detailed information about that component is readily available in the building manual. The manual can also help educate the occupant on how to best maintain and maximize the use of their home.

As mentioned previously, the power of parametric design and CNC fabrication allows the designer to be able to work with an extensive kit of unique structural and architectural components at a controlled cost. At the start, base geometries are defined for the minimum components needed to design the structure. From the base geometries, dimensions and parameters are manipulated to derive an infinite number of possible

[84] Bryant Rousseau, "The ArchRecord Interview: SOM's Garl Galioto and Paul Seletsky on BIM," *Architectural Record*, http://archrecord.construction.com/features/interviews/0803SOM_BIM/0803SOM_BIM-1.asp (accessed March 9, 2008).

variations. These variations of the base components should not cost much more to build if the method of fabrication is developed to be able to accept changing parameters. In the case of basic CNC fabrication, this is relatively straightforward, as the computer will be able to make adjustments to the cutting path and properties of the tool. In the case where a form or jig may need to be constructed for the fabrication of the parametric component, the fabricator can either build a more complex singular adjustable form or multiple ones associated with each variation.

While prefabrication traditionally relies on standardized systems, dimensions, and modules, parametric design helps eliminate redundancy and repetition within the overall design. In the past, a prefabricated system might attempt to create a universal component with fixed dimensions that could be repeated over and over. For example, a modular system would use the maximum transportable size on highways as the driving dimensions for modules while a panelized system might use the standard dimensions of plywood to determine panel sizes. With modern prefabrication technology, this is no longer a restriction for the designer. Although the variations of a parametric component might have the same basic shape and form, they are sized and shaped appropriately to their intended function and use within the overall building. This eliminates structural redundancies and inefficiencies, awkwardly scaled spaces, and undesired monotony in the final product. The architect is given a greater degree of freedom in design and is able to easily adapt the parametric system to a wider range of programs and sites.

The flexibility afforded by a prefabricated digitally designed parametric system is also a strong sales and marketing interface for these homes. Initially, the architect can use the system to efficiently design several building typologies and unique variations within the typologies. For example, a series of townhouses or a series of high-rise units can be developed from the same system. After developing a set of designs covering various site and program possibilities, a website interface can be developed to help prospective buyers select and configure the appropriate house for their site and needs. For the individual buyer who owns a site, the website would step them through a series of questions regarding the features of their site and their programmatic needs. Based on the information they provide, they will be presented with recommended typologies and possible configurations. After selecting a preferred configuration, they can customize the interior finishes as well as add or remove features. Because each component in the BIM model will have material and cost information embedded within, a price estimate for all configurations, interior finishes, and features can be quickly and easily updated. For potential developers of larger complexes or high-rise buildings, the website interface can help filter through various unit layouts and overall building and site configurations to meet their needs. The level of information provided by the website will far exceed what potential buyers can typically find out about homes or developments online. This allows the customer be much more knowledgeable about the product, cost, and options when it comes time to speak to the architect and refine the design. All of this functionality is driven by flexibility inherent in the prefabricated system as well as the embedded information in the BIM model.

The planning involved in designing and constructing a modern prefabricated building is much more comprehensive and detail-oriented than typical construction, where changes and adjustments are often made on the fly. Designing a prefabricated building therefore requires a larger amount of time and resources upfront. This larger investment upfront is offset by significant savings in construction length and the reduction of on-site errors and changes. Below is a summary of the advantages of modern prefabrication:

- Work with consultants, suppliers, and fabricators will be simplified by utilizing a central and shared building model that has detailed information embedded within it. By referring to this model, any party involved can determine the exact dimensions of a part, who is responsible for providing the materials and fabricating it, and how it will be assembled on site.

- The on-site construction process is drastically simplified when employing prefabrication processes. Rather than deliver raw materials to the site for construction, building components of various sizes and degrees of completeness are delivered to the site. The building is assembled like a piece of furniture rather than built from the ground up, which ensures a higher level of precision and accuracy, faster construction times, and fewer on-site construction mistakes.

- In the factory, components are modeled precisely on computers and tested and analyzed before fabrication. Once the designed component is ready for fabrication, the cutting information is sent from the digital file to a CNC machine, where the automated machining of the part is fast, precise, and consistent. Building parts should fit together seamlessly, minimizing air and water infiltration through joints.

- Less construction waste will be produced since much of the fabrication work is being done in a controlled factory environment. Material cuts will be arranged for maximum usage and leftover materials can be easily reused to make other components. This is important in Oahu where materials are already more expensive than in other parts of the country. Little transportation will be required to remove construction waste from the site.

- A variety of materials can be used and prefabricated to building housing in Oahu. Wood and steel can be cut with a variety of CNC milling machines, routers, drills, water jets, and more. Concrete can be prefabricated by cutting negative molds out of foam to bring to the site for on-site casting.

- Modeling the building on BIM software will also allow for simple exporting to environmental analysis programs. Factors such as the sun, wind, and rain water can be analyzed to study shading, shadows, wind conditions, natural daylighting, natural ventilation, drainage patterns, and more. This level of analysis can quickly identify problem areas in the design that need to be modified.

- Several variations of a basic design can be quickly fabricated, allowing for mass customization. Interactive media processes can help homebuyers customize the home to their needs, resulting in a home that better meets their functional living requirements. This also allows buyers to customize their home to fit their budgets by giving them a real-time update of how much the house will cost based on the features they have selected. Furthermore, it helps educate them about the advantages of the prefabrication process and the high quality features that the home includes.

- Cost will be better controlled because it will be known in advance how much the materials and manufacturing of each building component costs in prefabrication. Cost information can be embedded in the building information model, allowing real-time cost updates to occur as the design changes. During fabrication, labor costs will be reduced because less skilled labor will be needed to assemble the final product.

- Replacement parts for custom made components will be easy to reproduce since the information to fabricate the house is stored in the building model. Thus it will be easier to maintain the house and also to upgrade components if desired.

- Modern prefabrication allows for less restrictions on design innovation due to CNC based manufacturing. Instead of being limited to standard components or having to develop a closed system of components, designs can easily be customized, fabricated and replicated. Complex forms are also possible to mill at a lower costs since they are no longer hand crafted and CNC technology is controlling the tooling paths.

While basic design principles cover many of the criteria identified for a quality home in Oahu, it is easy to see how modern prefabrication technology can make the entire process more efficient, comprehensive, and cost-effective. This additional level of detail and control given to the architect will help them achieve great designs at low costs. Careful planning of the prefabrication process from start to finish is essential for a project of this type to succeed. Furthermore, there are several technologies, tools, and processes that require time to understand and master in order to successfully implement them in a real project. However, given that it is a logical direction for home construction to move towards given the modern prefabrication technologies available today, forward thinking architects that want to get more involved in residential design should not hesitate to begin integrating some of these technologies into their practice.

5.4. Design: Problem Statement

The Oahu Townhouse Prototype intends to provide a housing solution for urban, medium-to-high density mixed-use neighborhoods primarily in Honolulu. Given the rapidly growing population, rising costs of construction, the limited availability of land, environmental impact of sprawl, and the relative unaffordability of homes, it is believed that Honolulu needs to develop mixed-use neighborhoods that can house more people, provide alternative options for home ownership, and reduce the reliance on personal automobiles. Townhouses are just one of many possible urban housing types that can help meet these goals. For this design prototype, townhouses have been selected because of their site configuration flexibility, simple program, small footprint, and the unique quality of sustainable urban life they can provide.

Because this is a design prototype with no selected site, a flexible program and minimum site restrictions must be established. This means that guidelines for buildable area, density, setbacks, height, and parking/loading requirements will be based on Honolulu's Land Use Ordinance for the appropriate zoning districts. Having met the minimum guidelines, the prototype will allow for a clear and simple expansion of units to accommodate larger sites. The intention is that potential owners or developers would be able to easily fit any configuration of townhouses to any typical sites in the specified zoning districts, with the buildings' connection to the ground and the overall site planning presenting the primary design challenges.

As the focus of the research has been on the utilization of modern prefabrication technologies in residential construction, the detailed design of prefabricated components and supply and assembly procedures on and off site will be documented. Technologies will be employed to provide a solution that provides a balance between design complexity and fabrication standardization. Materials and systems will be designed and selected based on characteristics such as reusability, recyclability, and structural efficiency. A technologically driven process will be developed to help market and sell the townhouse prototype to the savvy customer that is targeted. The overall goal of designing these systems and processes will be to introduce an innovative, quality-driven, efficient, economical, and sustainable solution to urban housing design in Hawaii. Quality will not only be defined by the resulting product, but also the design and construction process and its operation and maintenance afterwards.

The basic single residential townhouse unit will comfortably house a typical family of four in an efficient 3 bedroom 2.5 bathroom multi-story layout. While no extensive cost estimates will be conducted, the goal is to provide a high quality townhouse at the median or lower price of a 3 bedroom home in Honolulu with low maintenance and energy costs. This will be achieved through a combination of increased density through design, construction efficiencies from prefabrication, and energy efficiencies from sustainable architectural features. Although no site is selected, Honolulu's climate will play a very important role in the design of a responsible and energy efficient townhouse.

In addition to a residential component, a key feature of the townhouse building design is to provide leasable retail space at the street level. The ground level retail space will contribute to the availability of conveniences in the mixed-use neighborhood. It will also establish a more active relationship and connection to surrounding buildings by promoting pedestrian activity in the area.

5.5. Design: Site Configurations and Massing

Within the proposed urban context for the townhouse, the prototype design will adopt a basic unit footprint and density that can be adapted and configured for a range of site sizes as defined under the City and County of Honolulu Land Use Ordinance development standards for Apartment Mixed Use (AMX) and Business Mixed Use (BMX) districts. In this section, three hypothetical sites will be examined relative to how the townhouse prototype units can be configured.

A single townhouse massing unit will be approximately 18 feet wide by 60 feet deep, with a footprint of 1,100 square feet. The building with have 4 stories plus an accessible rooftop and will have a height of 50 feet at its highest point. The residential component within the building will have an area of 2,200 square feet and the ground level retail space will have an area of 850 square feet, giving the building a total interior area of 3,050 square feet. The intent of these example site configurations is to display the townhouse units' flexibility and ability to adapt to various sites. In all site layouts, sustainable efforts such as maximizing open space, increasing ventilation through massing, and reducing heat island effects will be employed.

The first site configuration and massing looks at a 5,000 square foot BMX-3 duplex lot, the minimum intended configuration for the townhouse prototype. This typical neighborhood lot would run 50 feet along the front facing the sidewalk and street and would extend 100 feet into the block. In this layout, two townhouses are placed side by side with a shared party wall in between, creating a footprint of 2,200 square feet that covers 45% of the site. BMX-3 lots do not regulate maximum building area, but in AMX sites, 50% would be the maximum lot coverage. The maximum height for a BMX-3 lot is typically anywhere from 60 to 150 feet in Honolulu and the height setback requires that no portion of the building should exceed a height equal to double the distance from the building to the vertical projection of the center line of the street. Assuming a 20 foot distance from the center of the street to the sidewalk and a sidewalk width of 10 feet, no height setbacks would be required until after 60 feet, which works with the 50 foot height of the townhouse unit. Overall, the density and Floor Area Ratio (FAR) of the building is only 1.2, well within the maximum FAR of 2.5 provided by BMX-3 districts.

The small size of the site requires that certain assumptions be made in order to provide an effective configuration with regard to automobile parking and access. Since the side-by-side layout of the townhouse units requires 36 feet of street frontage, 14 feet of space is left for side yards. This is enough for a private one-way driveway on one side of the property for front to the back parking access. However, providing this access requires that the property is declared a duplex lot and shares a wall and zero yard setback with the adjacent property to the west. Otherwise, if this driveway were not provided for the narrow 50 foot by 100 foot site, a back alley access would need to be built.

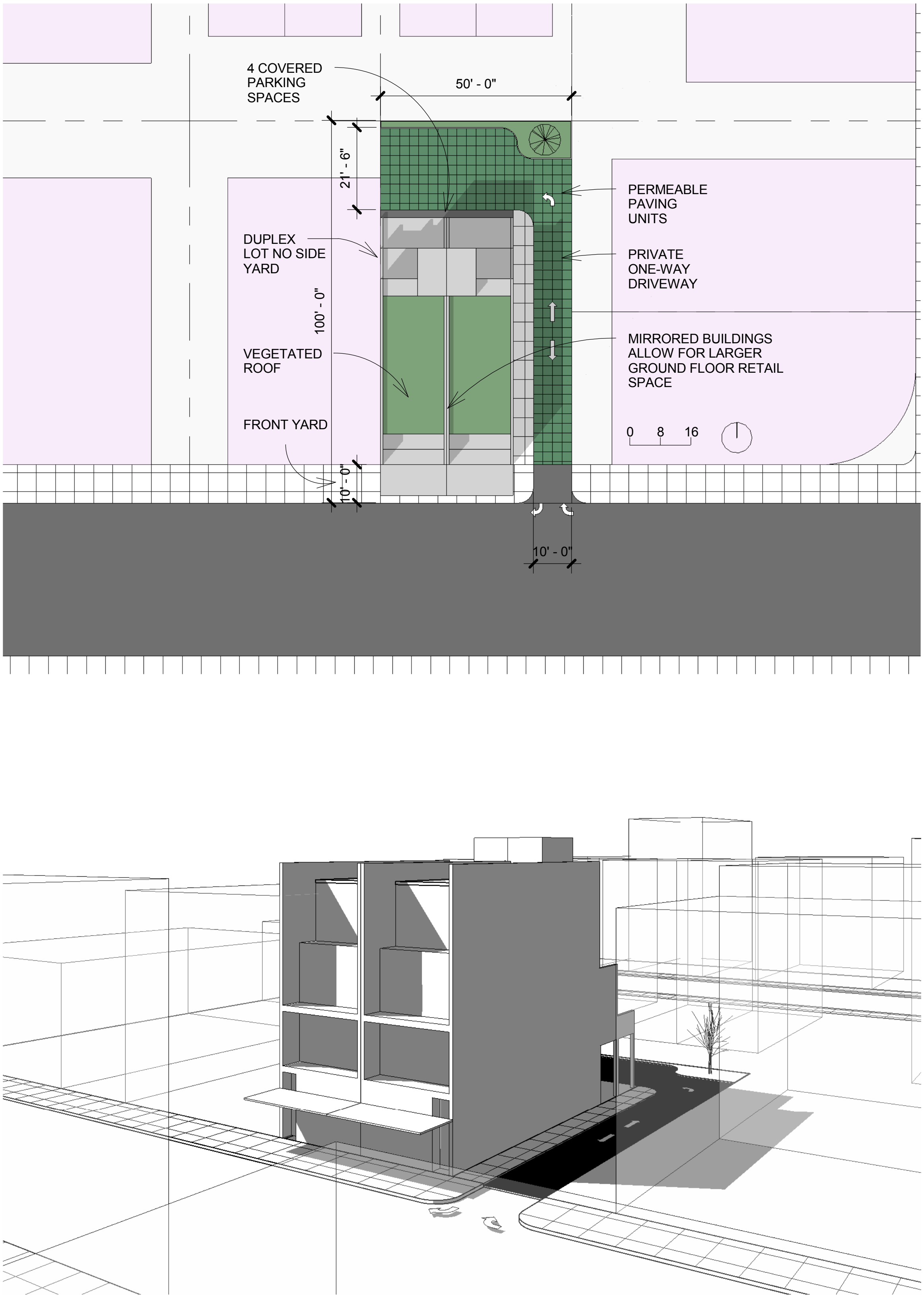


Figure 5.3. Site Configuration for 5,000 Square Foot BMX-3 Duplex Lot

While the residential parking requirement is met within this small site configuration, there is no space leftover to provide retail parking. With 1,700 square feet of retail space, 5 parking spots are required by code. However, because this is intended to be a small infill site in a tight urban context, it will be assumed that parking for retail is offloaded to a nearby parking lot or structure, a common solution for urban areas where small building sites may have trouble supporting expansive parking lots. Alternatively, if the townhouse buildings are located near public mass transit systems, there is precedent that parking requirements can be reduced. Cities like Seattle and Portland have recently reduced or eliminated parking requirements altogether for areas located near light rail stations[85].

This first site configuration shows that two 3 bedroom 2,200 square foot townhouses with 1,700 square feet of retail space below can effectively fit on a small infill site of only 5,000 square feet. It would be extremely difficult to fit two typical single family homes of equivalent area on a site this small, let alone additional retail space and parking. Space for parking and driveways present the most difficult challenges for this site configuration. With flexibility in parking options or deployment in a neighborhood adjacent to a mass transit system, it can be a viable solution.

The second site configuration and massing examines a larger 12,500 square foot AMX-2 lot. As in the previous configuration, townhouses are laid out side by side, sharing party walls in between and fronting the street to create a stretch of retail spaces. In this 100 foot wide by 125 foot deep lot, four units are provided and all development standards are met, including the required yards and parking and loading requirements. The lot coverage area is 35%, less than the maximum 50% allowed for AMX-2 and AMX-3

[85] Linda Baker, "No Parking: Condos Leave Out Cars," The New York Times, November 12, 2006, http://www.nytimes.com/2006/11/12/realestate/12nati.htm (accessed March 31, 2008).

zones. The maximum height will be in the same 60 to 150 foot range as the BMX-3 zone. Height setbacks are required for the side and rear for any portion of the structure above 40 feet. Because the primary portions of the townhouse units that exceed 40 feet are set further into the site, height setbacks are met. The FAR is approximately 1.0, which is below the maximum of 1.5.

In addition to the 8 covered parking spots provided for the residents, 10 parking spots and a loading zone are included on the site for the retail. An access road takes cars from the front of the site to the rear where all the parking is provided, while the loading zone is located at the front of the site near the retail entrances. This configuration provides a conservative site layout that meets all code requirements for the zoning district but does not waste any space. Its density is lower, but the site is fully utilized to provide four 2,200 square foot townhouses, a total of 3,400 square feet of retail space, and all the parking and loading requirements.

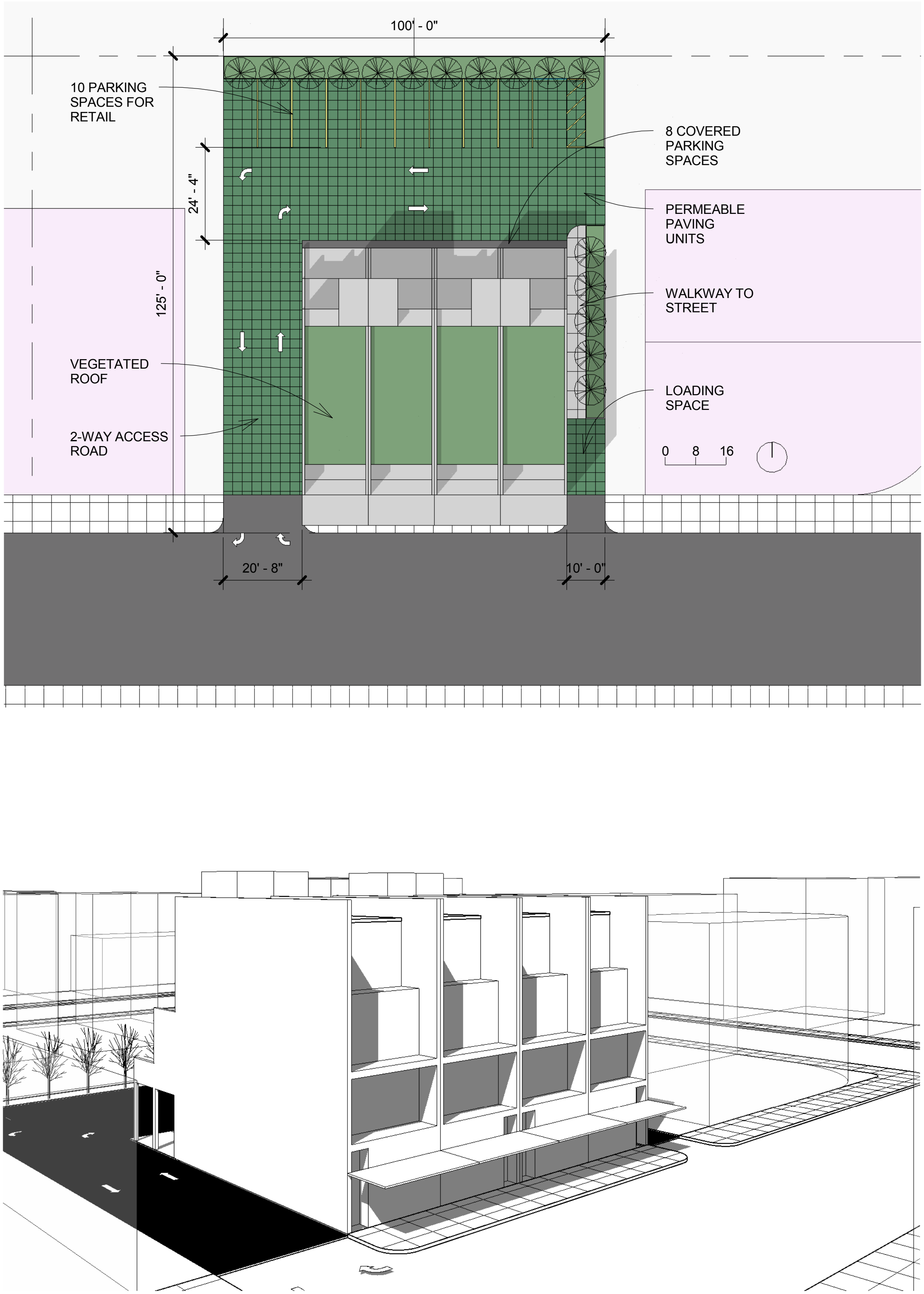
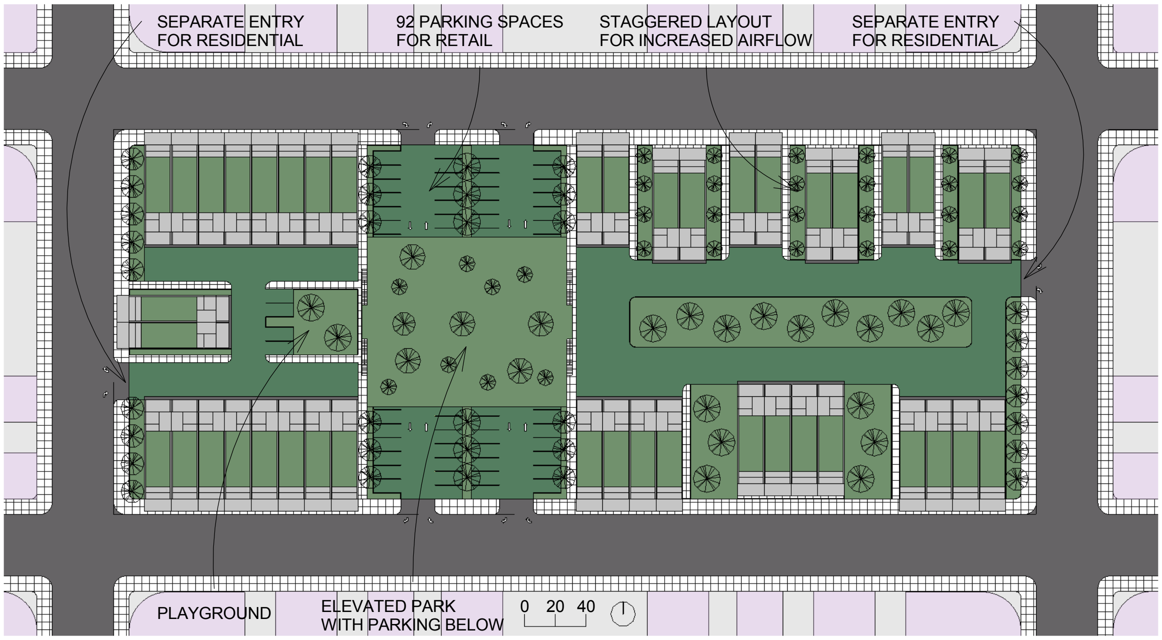


Figure 5.4. Site Configuration for 12,500 Square Foot AMX-2 Lot

The third site configuration examines a larger development of 150,000 square feet and is suitable for either AMX-2, AMX-3, or BMX-3 development. The size of this development is a typical city block in Honolulu, measuring 600 feet by 250 feet. The retail spaces front the sidewalks and streets creating a pedestrian oriented interface, while internal vehicular circulation is placed in the center of the block. This townhouse development includes two main groupings of townhouses which each have their own private entries separate from the retail parking entrances. A total of 42 townhouses are included in the complex, covering approximately 30% of the site and having an FAR of 0.9. The retail parking is located between the two groupings and is covered by an elevated park that serves as a public green space. This feature increases the amount of open space in a dense development, reduces heat island effect from large paved parking surfaces, and helps manage storm water runoff. On the northeast portion of the site, the townhouses are staggered to increase the flow of northeasterly trade winds. The spacing of the staggering is narrower at the windward side, causing the wind to accelerate through the gaps and increase ventilation through the massing.



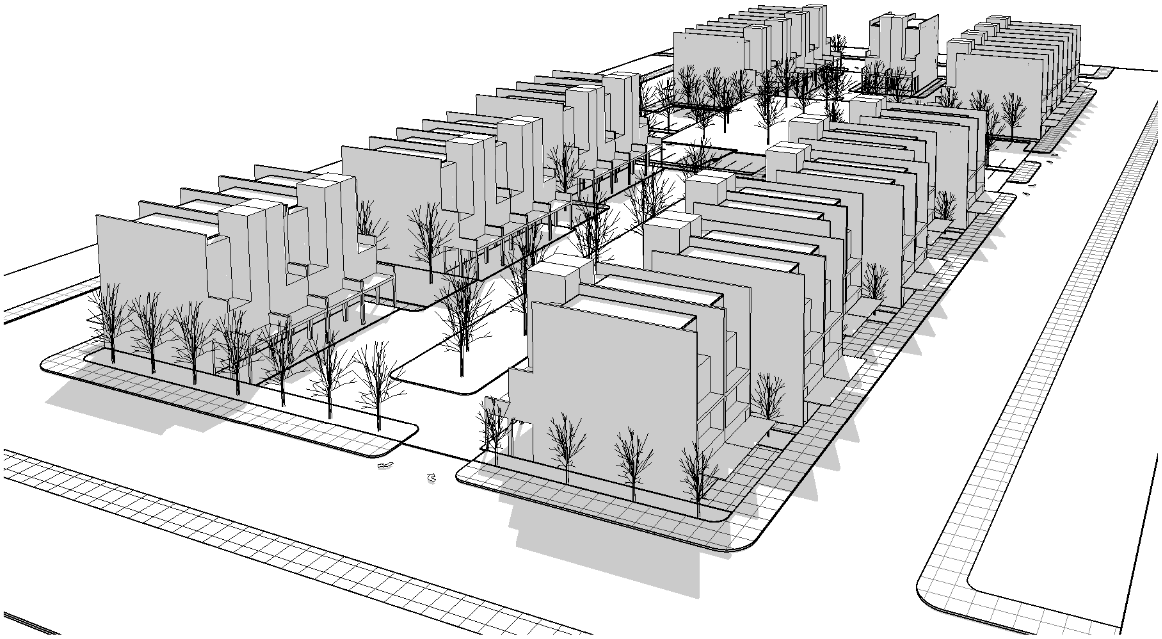


Figure 5.5. Site Configuration for 150,000 Square Foot Development Lot

While greater densities can probably be achieved with high-rise development on a site of this size, this configuration is intended for areas with lower height limits. This type of townhouse development is rare in Honolulu and would produce a unique and welcome mixed-use quality of living that is more suitable to medium density, pedestrian oriented urban neighborhoods. In future studies of this type of complex, it would also be important to design a variety of additional townhouse configurations and mid-rise or high-rise configurations to include in the master plan. This would provide a more interesting and heterogeneous mix of housing that could attract a greater diversity of residents.

Through these three massing studies, it is easy to see that the simple form of a typical urban townhouse can be adapted to a variety of sites and conditions. Whether it is a small infill site or a larger townhouse development, the prototype unit is flexible enough to stand on its own or it larger groupings.

5.6. Design: Concept

As described throughout this project, modern prefabrication technology will provide the means for a townhouse design solution that strives for the highest quality in fabrication and construction, form and function, monetary value, energy performance, durability, and indoor environmental quality. The ideas and values of prefabrication will be applied from design conception to completion to thoroughly illustrate what can be achieved.

Where most design projects begin with abstract investigations of spatial organization schemes relative to a site and program, a prefabricated project concurrently starts with the ultimate fabrication techniques and the exploration of how the structural system can be componentized. The typical design process in architecture takes on a top-down approach, where larger concepts are fully understood before delving into the details of construction and finishing. When including prefabrication as a primary design consideration, the architect must conceptually start from both the top (site, program, massing) and the bottom (fabrication, assembly, materials) with the goal of arriving at a solution in the middle. This is challenging, as simultaneous adjustments to both sides constantly generate new problems and conflicts. The design process is on a continuous feedback loop until a well balanced solution is found. In the end, this necessary back and forth interaction between abstract and technical considerations will often result in a robust and thorough solution.

Decisions must be made right away about how the overall volumetric and spatial elements of design will be broken down into prefabricated components before these volumes and spaces are even designed. Should the design take a modular, panelized, or pre-cut approach? What is prefabricated off-site and what is constructed or assembled on-site? How are prefabricated components shipped to the site? How are components assembled and connected together on-site? How does the assembly of these components create the desired interior spaces and exterior envelope of the building? These are all questions that will affect the design of each prefabricated component and ultimately what can be achieved in the overall design.

For the Oahu townhouse prototype, a prefabricated panelized approach will be used. In weighing the various options, this approach seemed to make the most sense for the design of a creative and adaptable structural system that took advantage of modern technologies such as parametric design and CNC fabrication. A modular approach would allow for more assembly to take place off-site but it would also limit variability within the overall system. Different configurations would simply mean rearranging large volumes of similarly proportioned space rather than having the ability to compose a more extensive range of unique spaces from smaller components, as an adjustable panelized system might offer. A precut approach also didn’t make sense because it would further limit the amount of off-site construction that could be done. The panelized approach perhaps combined with some prefabricated modular components will provide the most effective and flexible prefabricated solution.

With a panelized prefabrication strategy selected, basic material and structure considerations need to be addressed. Most prefabricated panelized approaches in residential construction today involve the use of structural insulated panels (SIPs), which are typically made by sandwiching a core of rigid foam plastic insulation between two structural skins of oriented strand board (OSB). The resulting composite panel acts as a structural I-beam or I-column, with the foam acting as the web and the OSB sheets as the flanges. These sandwich panels are prefabricated, structurally efficient, provide excellent insulation, and can be cut to custom sizes. They can be used in floor, wall, and roof applications.

While SIPs offer a well-known and reliable solution to panelized prefabrication, this project seeks to explore alternative panel compositions that can provide more flexibility in form and durability. In Hawaii’s warm, humid climate, wood is especially susceptible to rotting and termites. Concrete on the other hand is a material that eliminates these weaknesses and also can be cast into various forms and shapes. By itself, concrete may be too structurally inefficient for horizontal spans and too heavy for the transportation required by off-site prefabrication. However, when used in a composite format with other materials, it is possible to create high-quality lightweight prefabricated panels that can act as structural elements. These concrete based panel products, known as structural concrete insulated panels (SCIPs) are available but have not been used as extensively as standard SIPs. The use of concrete also allows for more exploration of three-dimensional panel forms due to its fluid properties before casting. It also becomes easier to build stronger elements by increasing the thickness of the concrete as the scale of the project rises. Custom designed flexible SCIP elements will serve as the primary prefabricated structural units for the design.

Figure 5.6. Factory Images of Prefabricated Structural Concrete Insulated Panels

In addition to providing a grounded prefabricated approach to housing design, this project also aspires to investigate innovative spatial concepts in residential architecture and push the boundaries of convention with the assistance of digital design technologies. Concepts and ideas generated from these explorations can add extra value and marketability to the home that would potentially offset any additional cost needed to execute them. The challenge is to find a balance between the simplicity and standardization necessary for fabrication processes and the opportunities for complexity and variation in spatial constructs. Any atypical or complex design elements introduced into the panels will still need to embody an internal logical that allows for a standard and repeatable method of fabrication.

With the exterior limitations set by the selected townhouse typology, it is more difficult to introduce form based changes in the exterior envelope. However, there is a rich opportunity to play with internal spatial forms to create an environment that enhances the lifestyle of the user. In the townhouse prototype, the idea of traditional flat horizontal surfaces in the house is challenged. It is argued that floors and ceilings that span wall to wall without depression or elevation present a lost opportunity for defining spaces, enhancing characteristics of proportion and scale, improving and framing views and sightlines, creating variations in spatial sequences, and providing additional functional surfaces for the user. Although lowered floors, raised ceilings, and double-height spaces are common elements to create the feeling of larger spaces in homes, they typically act as singular celebrated spaces within the overall context of the home. Instead, it is possible to break the plane of flatness more subtly and consistently throughout the home, allowing all rooms to benefit from the elevation variations. In multi-story applications, the effects on the ceiling below a lowered floor or the floor above the raised ceiling become opportunities for design. From a functionality perspective, changes in the elevation of a horizontal floor can be utilized as surfaces for seating or display, essentially acting as built-in furniture.

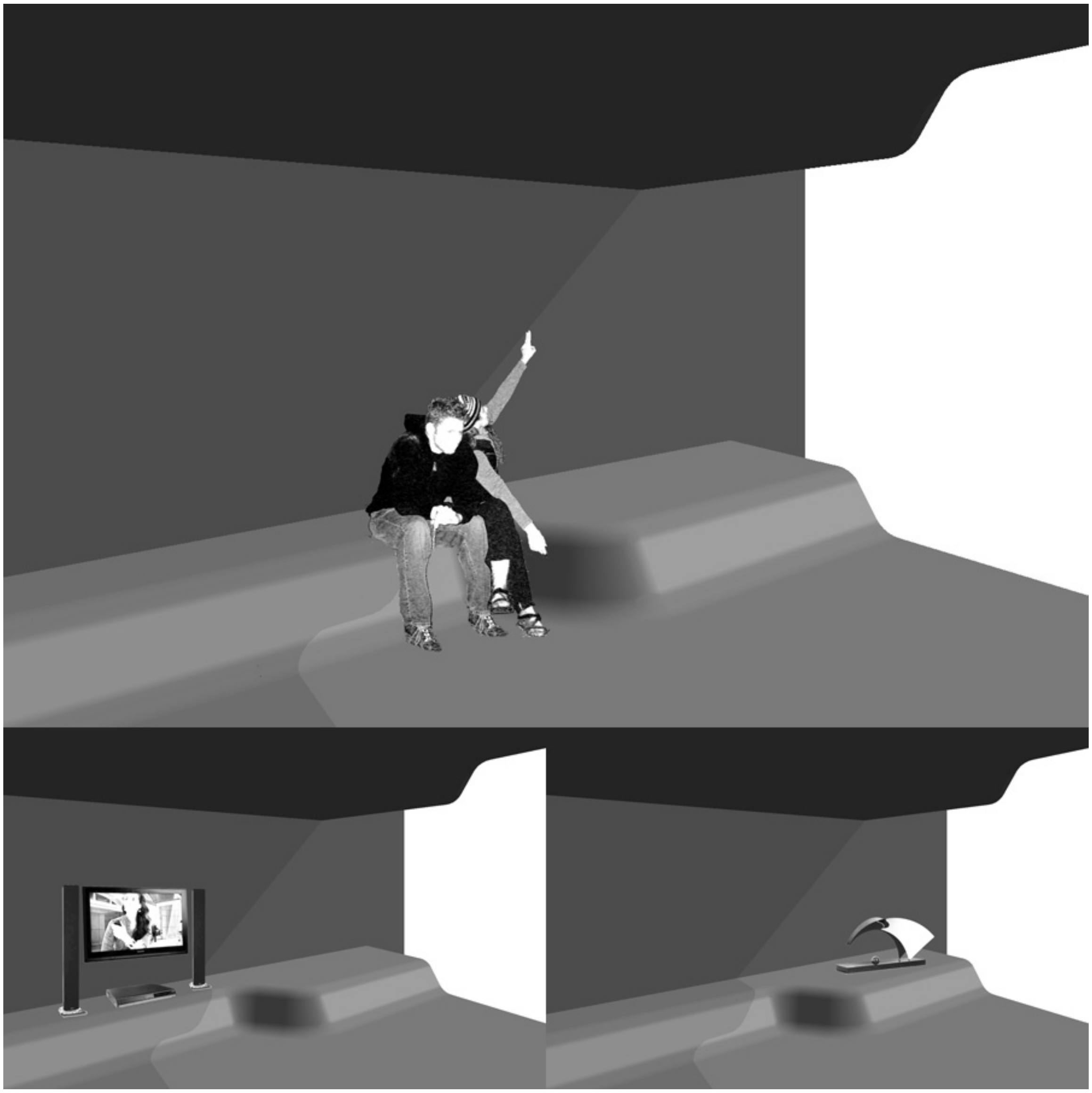


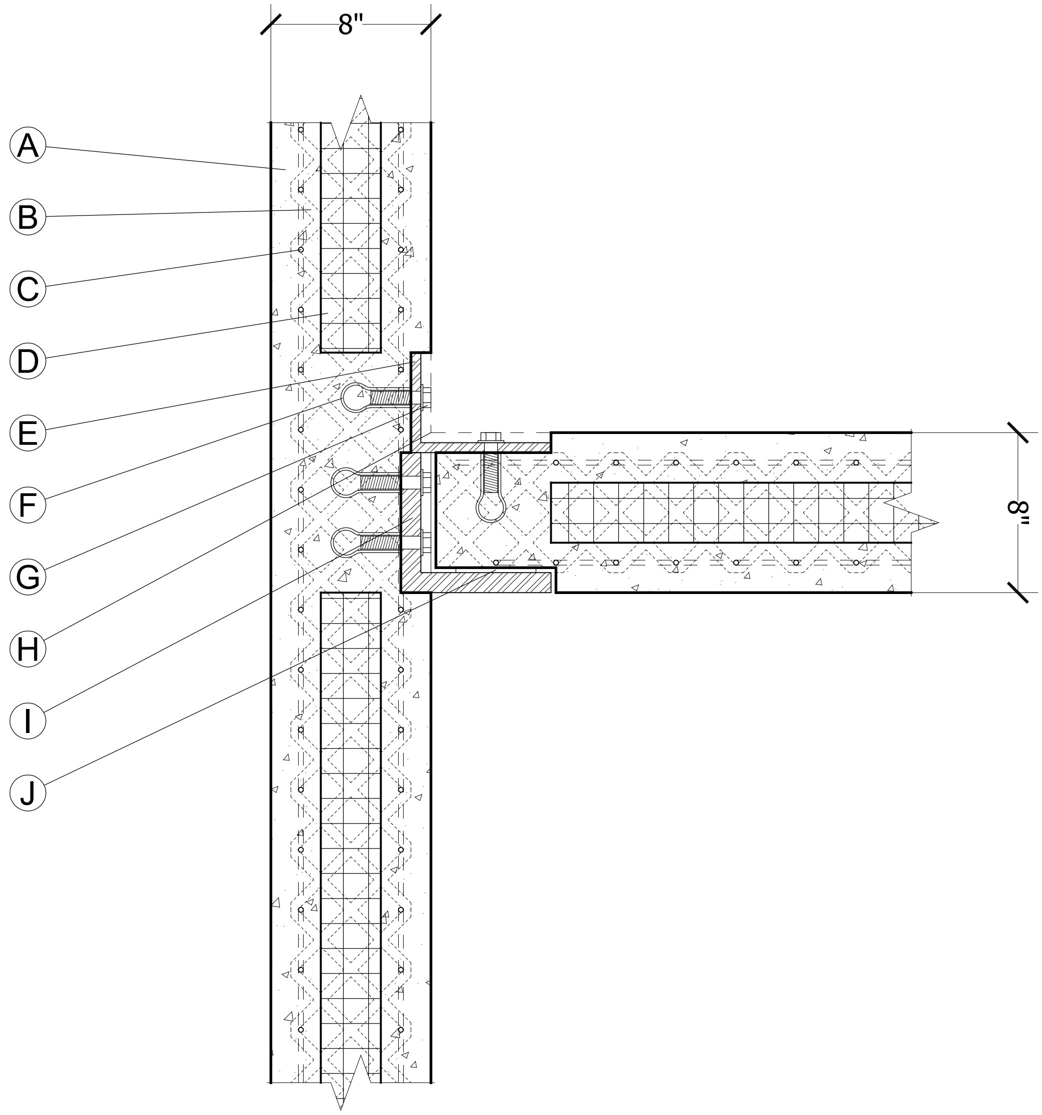
Figure 5.7. Examples of Uses for Elevation Changes in Floors

The natural landscape contains many examples of elevation changes that contribute to the beauty and interest of the three dimensional world. If it is possible to integrate logical and non-arbitrary elevation changes into the floors and ceilings of a house and also determine a rational method for the fabrication of these horizontal elements, then a strong case can be made for including "landscaped" floor and ceiling elements in the design. The intention is not to randomly introduce these elevation changes as non-functional creative art, but rather to enhance the space through increased functionality and a grounded aesthetic common sense. Flat surfaces within the housing design will not be eliminated but instead emphasized as defining elements within a larger spatial concept.

5.7. Design: Prefabricated Panels

The entire structural system for the townhouse prototype will primarily be developed from only three basic building component geometries. Two of these components are floor panels and the third component is a wall panel. Approximately 60 unique building parts will be derived from these three base geometrics through an assortment of parametrically driven variations. Both the wall and floor panels will utilize the same structural concrete insulated panel (SCIP) system. These panels will be prefabricated in a factory setting and then shipped out to site for quick assembly. Through a non-permanent connection system, the panels can also be disassembled and reused, allowing most of the building components to enjoy a lifecycle beyond the initial structural assembly.

The SCIP system is composed of a 3 inch expandable polystyrene (EPS) layer of rigid foam insulation sandwiched between two 2.5 inch concrete wythes. Panels for the townhouse will therefore have a total thickness of 8 inches. Within this composite panel, a variety of reinforcement elements are included. Embedded into both concrete wythes will be a steel welded wire mesh reinforcement element. The mesh is located about 1.5 inches into the concrete layers and helps provide tensile strength to the concrete and prevent cracking. Running length-wise with the panel are two or three carbon fiber shear trusses embedded in a bed of concrete that runs through the thickness of the panel. These trusses span the thickness of the panels and tie the two layers of mesh together, helping the panel resist shear forces and creating an integrated structural panel system. Additional beds of concrete spanning the thickness of the panel are located at points in the panel where connection elements are embedded.



Parts List:

- (A) 2.5 in. concrete wythe
- (B) Carbon fiber shear truss beyond
- (C) Steel wire mesh reinforcement
- (D) 3 in. EPS foam insulation
- (E) Steel panel to panel connection plate
- (F) Loop threaded insert
- (G) Bolt and washer
- (H) Connection covering panel
- (I) Steel corbel
- (J) Neoprene bearing pad

Figure 5.8. Wall and Floor Panel Connection Section Detail View

The EPS insulation core used is called Neopor and is developed by the chemical company BASF. Neopor is a significant advancement on Styropor, a common EPS product that is also developed by BASF. Using microscopic flakes of graphite in the composition of the foam that reflect heat radiation, Neopor is able to provide the same insulating performance as Styropor with up to 50 percent less raw material[86]. Styropor has already been commonly used in SCIP applications, and Neopor can help further reduce the thickness of panels. Because EPS is an inert, organic material, it will not rot, is highly resistant to mildew, and provides no nutritive value to plants, animals, or microorganisms. Both EPS materials are also composed of recyclable resins and have been certified as low-emitting materials, thus giving them characteristics of sustainable and healthy materials[87].

To create strong and highly durable concrete wythes, Fly ash will be used to replace up to 30% of the Portland cement in the concrete. Because fly ash is a by-product of coal-fired electric generating plants, it serves as a recycled product in concrete. In addition to the fly ash, plastic fibers will be added to the concrete to provide additional tensile strength and reduce the amount of concrete necessary in the panel. The concrete wythes will also be polished so that the panels are given finished interior surfaces. This will eliminate the need for finishing material like drywall, tiles, carpet, wooden flooring for most of the interior surfaces unless specified. In most spaces, the floor panels will act as both a finished floor and finished ceiling for the space below, saving cost on flooring and ceiling finish materials.

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[86] "Neopor," *BASF Group*, http://www.corporate.basf.com/en/innovationen/preis/2001/neopor.htm (accessed April 3, 2008).
[87] "Styropor EPS for Green Sandwich Building System," *The A to Z of Building*, http://www.azobuild.com/news.asp?newsID=2061 (accessed April 3, 2008).

Where many SCIP panels use a steel welded-wire truss for shear strength, these panels will employ the use of carbon fiber trusses. The precast concrete company Altus Group has developed a SCIP panel product called CarbonCast that utilizes carbon fiber shear trusses. The truss is a grid of carbon fiber that is set perpendicular to the two concrete wythes, tying the three main layers of the panel together to form a unified system. The carbon fiber truss is non-corrosive and has over four times the tensile strength of steel reinforcing[88]. This results in a highly durable, efficient, and lightweight reinforcement element in the SCIP panels. Also, unlike steel, the carbon fiber does not conduct heat, improving the insulation qualities of the panel.

Based on similar SCIP panels, it is estimated that the 8 inch thick wall and floor panels will have an insulating R-value of somewhere between 30 and 40. According to the U.S. Department of Energy's Energy Star website, in a warm climate with minimal heating requirements, floors and walls are recommended to have values of R-11 to R-13, while ceilings should have values of R-22 to R-38[89]. Thus, the designed SCIP elements will provide sufficient insulation in addition to their efficient structural characteristics.

The material choices within the SCIP system reflect the desire to minimize the amount of material needed to create a durable structural wall or floor panel element that has excellent structural, thermal, and acoustical performance. High-tech modern materials will typically cost more, but they also require less material quantity and provide lifecycle savings due to their higher energy performance and durability. Achieving the structural

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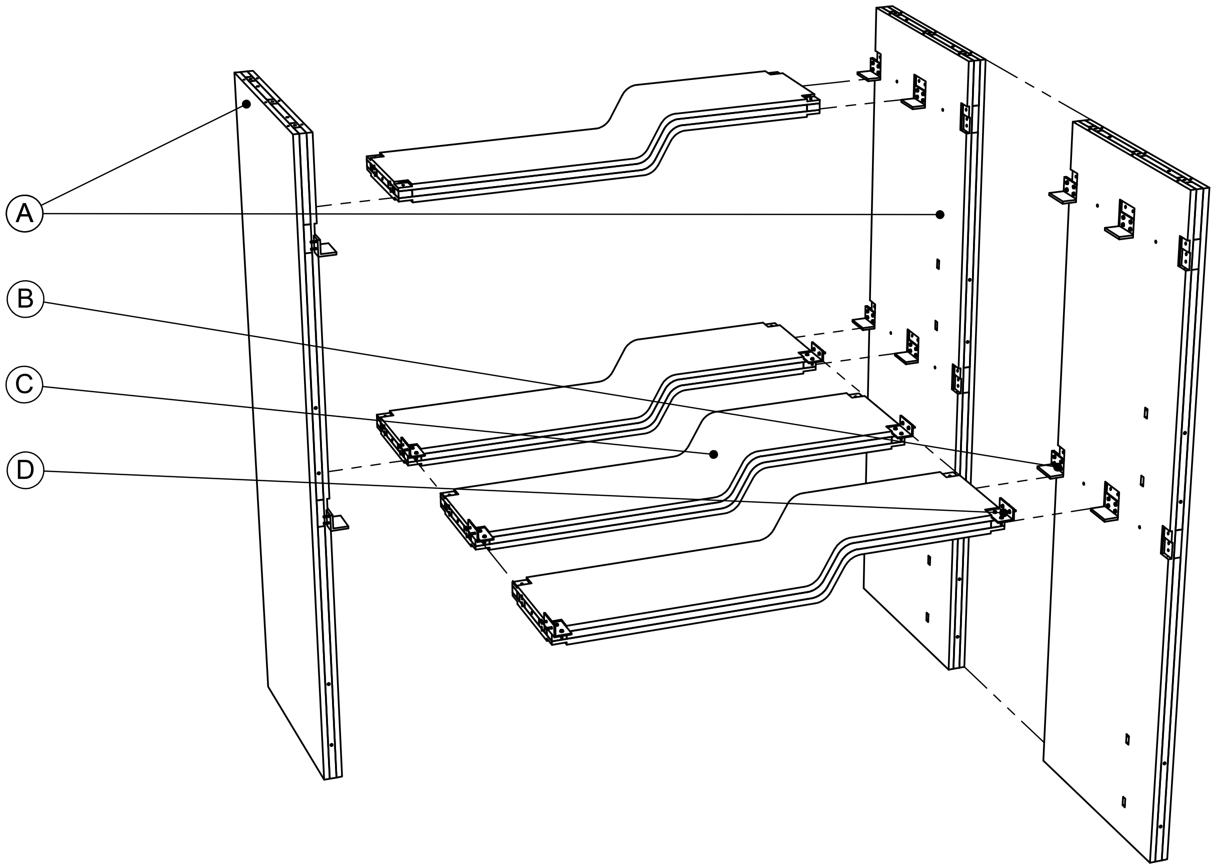
[88] "High Performance Insulated Wall Panels: CarbonCast," *Altus Group*, http://www.altusprecast.com/uploads/1137682951/Downloads-PDF-Docs/AG_IWP_brochure20d.pdf (accessed April 3, 2008), 3.
[89] "Recommended Levels of Insulation," *Energy Star*, http://www.energystar.gov/index.cfm?c=home_sealing.hm_improvement_insulation_table (accessed April 3, 2008).

efficiency is especially important for the transportation of the prefabricated panels. Without the reductions in volume and weight that these materials and systems offer, the panels would become too difficult and expensive to transport. If upfront costs do need to be reduced, there are some alternatives that can be used within the system, such as replacing Neopor with Styropor in the EPS insulation or replacing the carbon fiber shear trusses with more typical steel welded wire trusses.

The layout of the structural system using these SCIPs is very simple, with typical wall panels extending vertically two stories and the floor panels sitting in between two wall panels on attached corbels. Dead and live loads on the floor panels will thus be transferred down to the ground through the structural wall panels. Using the parametric modeling capabilities of Autodesk Revit and Dassault SolidWorks, the three base panel families and all of their derived variations can be precisely defined.



Assembly Process:

(A) Wall panels are set in place on foundation.

(B) Steel angle corbels are bolted to wall panels and also act as connection plates to bolt wall panels together.

(C) Floor panels are set in place resting on steel angle corbels.

(D) Steel connection plates are attached at the joint allowing floor panels to be bolted to each other as well as to the wall panels.

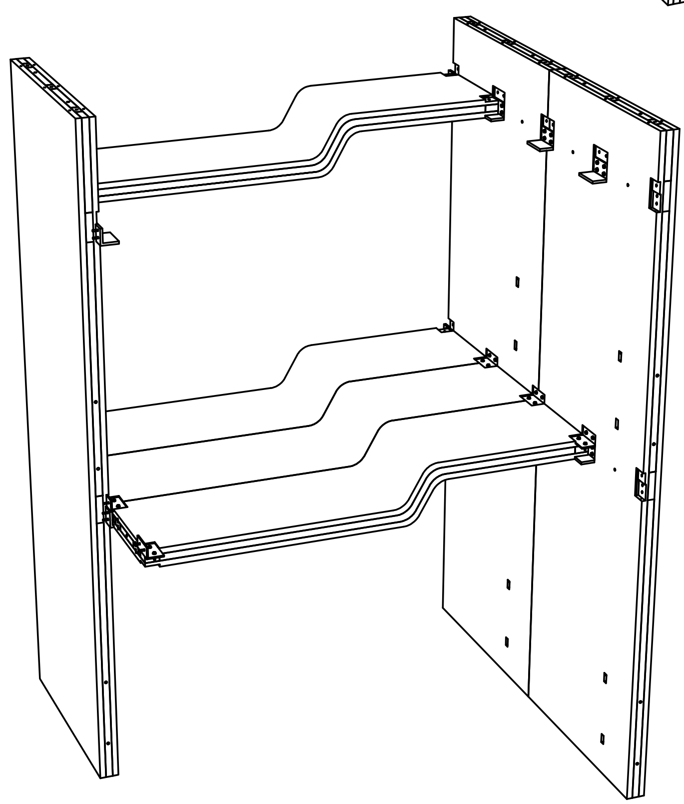
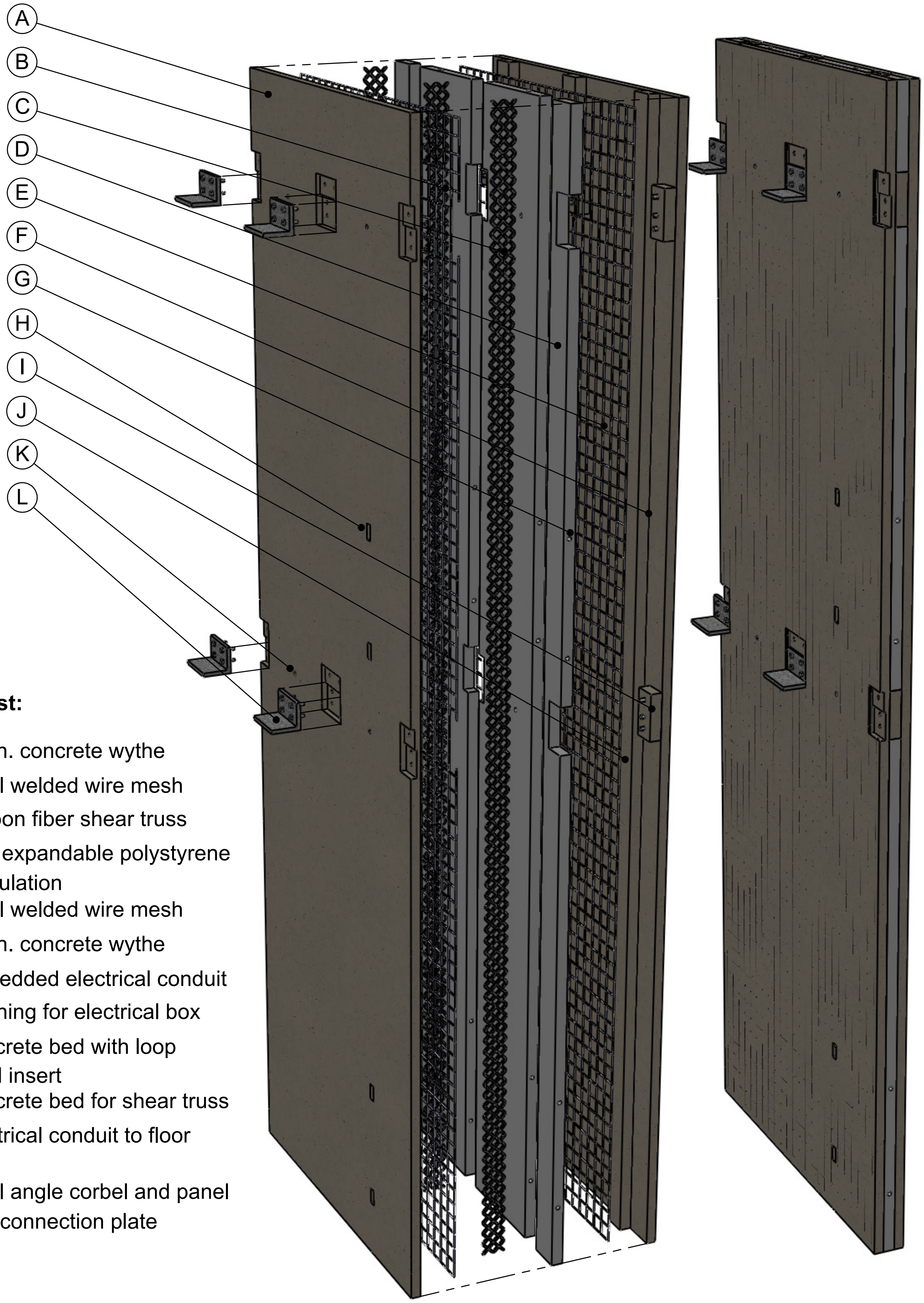


Figure 5.9. Exploded Perspective View of Wall and Floor Panel Assembly

Wall panels within the system are given a maximum size of 8 feet wide by 24 feet tall by 8 inches thick. This allows the walls to be stacked on a flatbed truck for transport. Within the parametric model for the wall panel family, dimensions can be adjusted and features added or removed. Besides the basic overall dimensions of the panel, the most significant parametric changes are the placement of the corbels on the wall, and the placement of openings on the wall. Because of the design of the multi-elevation floor panels, it is important that the corbel positions can easily be adjusted when fabricating the wall panels. Parametrically specified openings will allow for windows and larger openings to be placed in the walls. The model will be intelligent enough to provide restrictions on where these openings can be placed so that the structural integrity of the panel is maintained. Within the single parametric model for the wall panel, all the dimensions and variables that drive each panel instance is stored in data tables. These tables can be quickly edited if new derivations need to be created or changes need to be made to existing wall panel types.

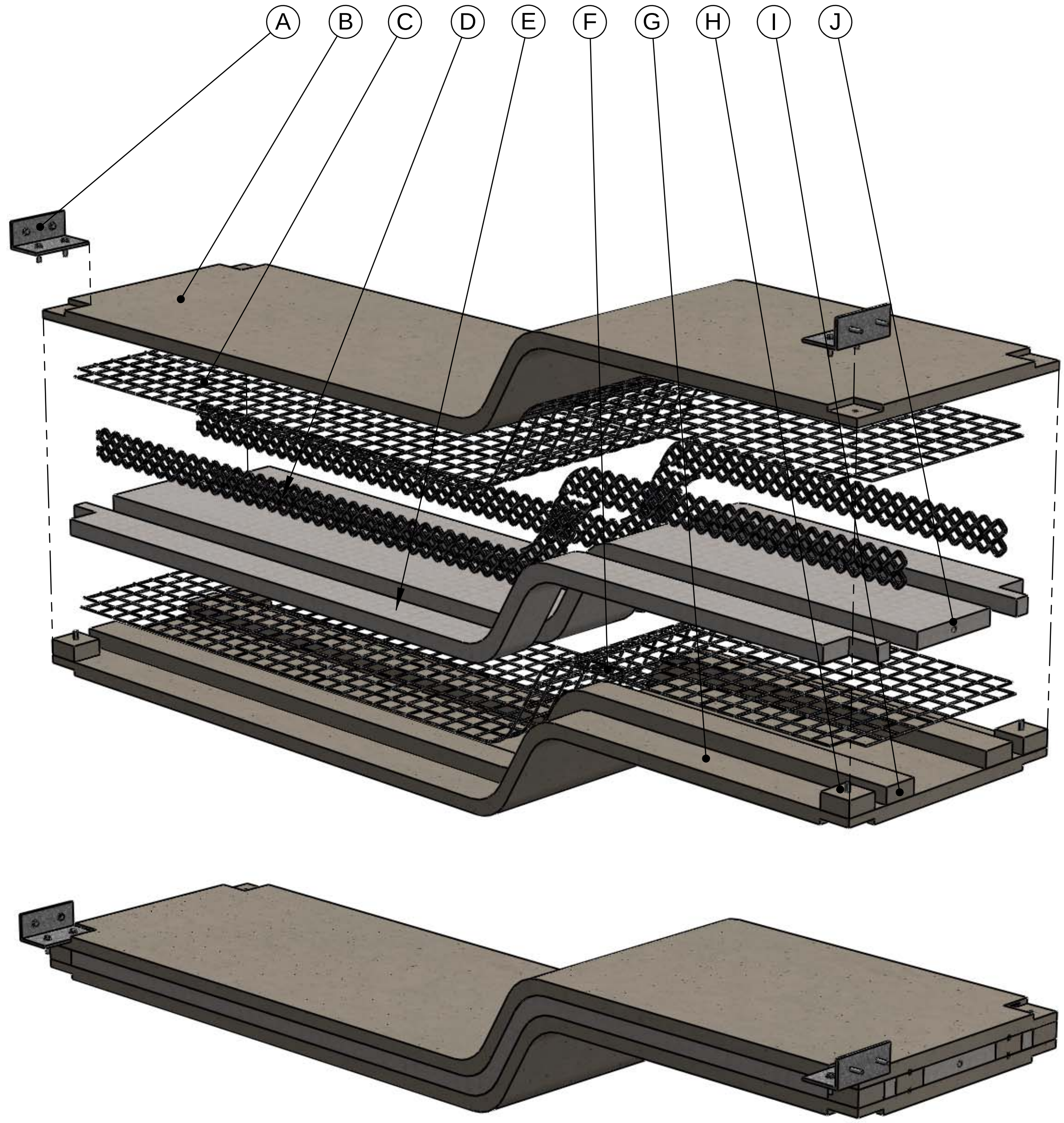


Parts List:

Ⓐ 2.5 in. concrete wythe
Ⓑ Steel welded wire mesh
Ⓒ Carbon fiber shear truss
Ⓓ 3 in. expandable polystyrene foam insulation
Ⓔ Steel welded wire mesh
Ⓕ 2.5 in. concrete wythe
Ⓖ Embedded electrical conduit
Ⓗ Opening for electrical box
Ⓘ Concrete bed with loop threaded insert
Ⓙ Concrete bed for shear truss
Ⓚ Electrical conduit to floor panel
Ⓛ Steel angle corbel and panel to panel connection plate

Figure 5.10. Exploded Perspective Detail View of Typical Wall Panel

The two floor panel base types for the townhouse prototype each have a maximum size of 4 feet wide by 16 feet long by 8 inches thick. Whereas the wall panels are designed to be straight, elevation changes are introduced into the floor panels to execute the concept of the “landscaped” floor and ceiling. Throughout the townhouse, a consistent elevation change of 1.5 feet will be included in the floor panels. This provides a human scale height change that is possible to traverse without the need for steps and is also the ideal height for seating or display. In the first type of floor panel, the elevation change occurs consistently at one point along the length of the panel. The second type of floor panel introduces a sweep feature along the width of the panel, where the point of the elevation change differs along a curving path. This type of panel is essentially used to connect two variations of the first type of floor panel. For example, the building might have a panel with the elevation change occurring 4 feet into the length of panel and another panel with the change occurring 6 feet into the length of the panel. To connect the elevation changes of these two panels, a sweep panel would be placed in between them that starts with an elevation change at 4 feet into the length of the panel and ends with an elevation change at 6 feet into the length of the panel.



Parts List:

- (A) Steel panel to panel connection plate
- (B) 2.5 in. concrete wythe
- (C) Steel welded wire mesh reinforcement
- (D) Carbon fiber shear truss
- (E) 3 in. expandable polystyrene foam insulation
- (F) Steel welded wire mesh reinforcement
- (G) 2.5 in. concrete wythe
- (H) Concrete bed with loop threaded insert
- (I) Concrete bed for shear truss
- (J) Embedded electrical conduit

Figure 5.11. Exploded Perspective Detail View of Typical Floor Panel

For both floor panel types, the parametric variations are primarily driving the location of the 1.5 foot elevation change. There is also a parametric feature where floor panels with vertical openings can be derived. This feature is used for skylights, atriums, and double-height spaces. Like the wall model, all the driving dimensions of the floor panels are stored in data tables that can be manipulated to derive new panels or edit existing ones.

A powerful feature of the parametric panel models described above is the ability to change even those dimensions that have been fixed for the purposes of the townhouse design. For example, while the elevation change in the floor panels has been set to a constant 1.5 feet, in another building application, this dimension can be increased or decreased, or the distance across which this elevation change takes place can be stretched out. Floor panel lengths can also be changed to create longer or shorter spans. If necessary, the thickness of the panels can be increased or decreased and the basic maximum dimensions can be adjusted. This ability to mass customize by creating a large number of unique panels from only three base models allows for a flexibility in design and configuration that was not previously attainable in prefabricated design.

The fabrication of all panels will be adapted from existing SCIP factory processes. Automated processes already exist for the fabrication of large SCIP panels, including the cutting of the insulation, the placement of the reinforcement, and the pouring and curing of concrete. At larger operational scales, it would be important to automate as much of the process as possible. The use of digital parametric models assists in this process by communicating dimensional changes and variations to the CNC based machinery. For the development of the townhouses, forms will be built for each of the three panel types. In a more automated approach, servomechanisms can be included which can take information from the data tables in the parametric models and automatically make adjustments to the form. For example, in the basic floor panel, a sliding mechanism can be placed where the elevation change occurs. Based on the dimension given for the panel derivation, the elevation change portion would slide to the appropriate location for casting. In smaller scale operations, the moving form can be manually adjusted instead of obtaining instructions from the computer model. Other panel components that will be digitally fabricated are the EPS foam insulation, the steel mesh, and the carbon fiber trusses. These elements, particularly when they curving in the floor panels, can be easily and precisely cut via CNC milling machines or laser cutters.

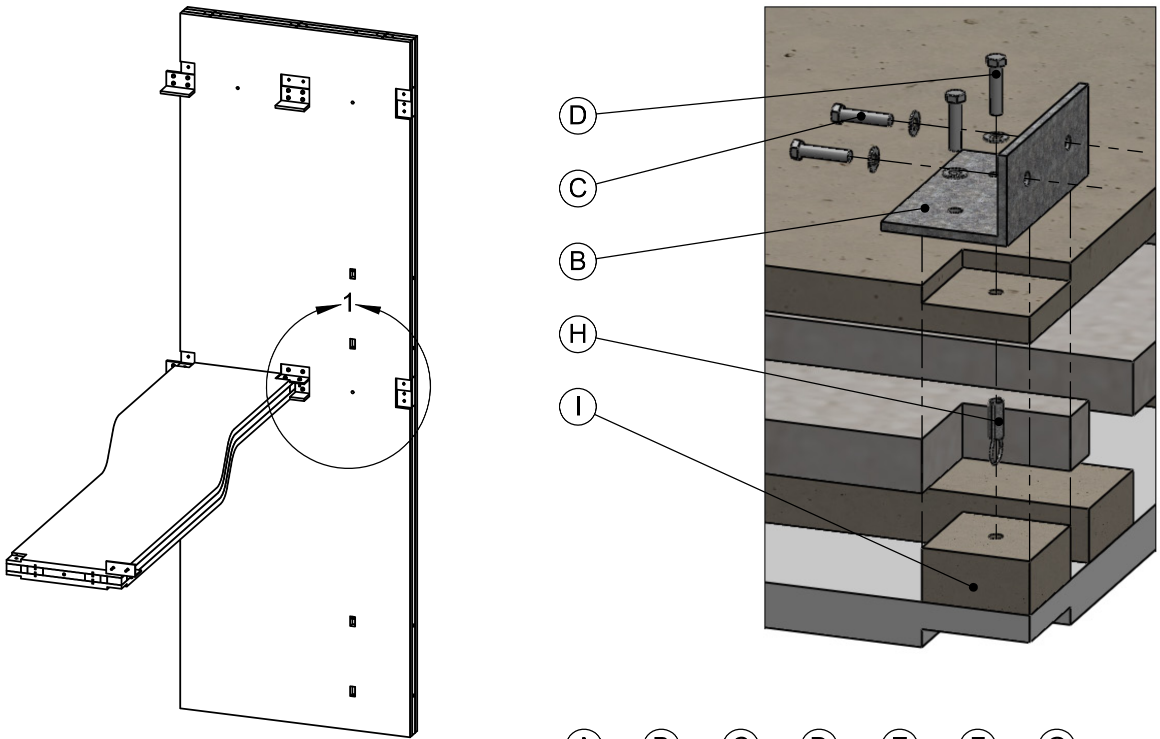
Figure 5.12. Section Model of SCIP Panel

Once the reusable adjustable forms are constructed and the insulation and reinforcing elements are cut, the composite panel is ready to be assembled. First, the form is modified to the dimensions and features of the panel to be built. For wall panels, the position where the corbels are attached is set and any openings are placed in the formwork. For floor panels, the position of the elevation change and any vertical penetrations are positioned in the formwork. Next, the CNC milled insulation, the carbon fiber reinforcing, the steel mesh, and the threaded inserts will be placed within the form at their proper positions. Because of the elevation change element in the floor panels, the form will be oriented vertically, in the direction of the 4 foot width. The concrete will be poured into the form, embedding the insulation, reinforcing, and connection hardware. After the concrete has been poured, the form can be vibrated to eliminate any air bubbles. Finally, the panel will be cured, polished and finished, wrapped for protection, and then shipped to site. All panels will be stackable, whether on top of each other or on their sides, to minimize the number of trucks needed to ship the components to the site.

By prefabricating the SCIP floor and wall panels in the described manner, the main structural system and most of the interior finishes can be built in a controlled factory environment. Digital fabrication methods help automate the process and also assist in the cutting of the curved forms and cutouts in the insulating foam. This results in a higher consistency and quality in the construction. Also, connections and tolerances can be tested in advance so onsite work can be completed quickly and efficiently.

5.8. Design: Connections and Assembly

One of the main concepts behind the connection and assembly process is the ability for the system to be disassembled so that the panels can be reused in another building. Additionally, reusable panels would support the expansion and reduction of the townhouse in the future if the owner's lifestyle or space needs ever change. Panel connections are therefore developed to be non permanent connections, using bolting hardware instead welds and grouting.



Parts List:
- (A) Floor Panel
- (B) Steel Connection Plate
- (C) Bolt to Wall Panel
- (D) Bolt to Floor Panel
- (E) Bolt to Wall Panel
- (F) Steel Corbel
- (G) Wall Panel
- (H) Loop Threaded Insert
- (I) Concrete Bed

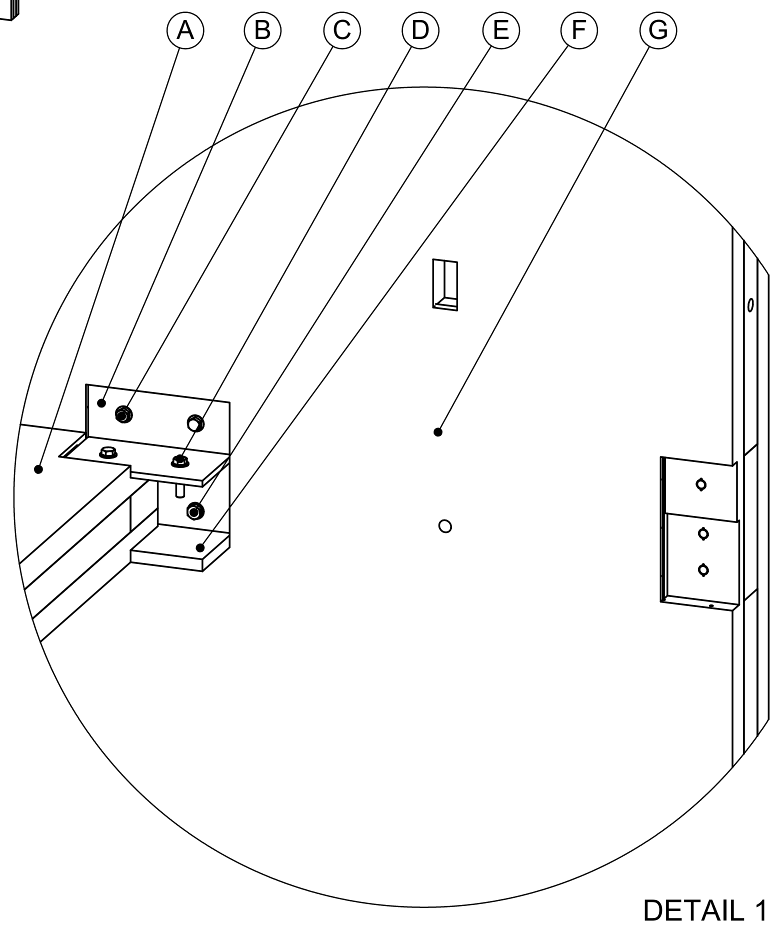


Figure 5.13. Dimetric Views of Panel Connection Details

In the wall panels, threaded inserts are cast into the concrete to support bolted-on corbels and connection plates. During the assembly of the building on site, these threaded inserts also double as the reinforced points where panels are lifted by cranes. The corbels attached to the wall panels are steel angle elements that are removable so the panels can be stacked during transportation. They are simply bolted to the wall panel once the panel has been positioned. When the corbels are bolted in place, they act as universal connectors that also join wall panels to wall panels. The entire system of threaded inserts, corbels, and bolts is thus able to address several assembly issues, including structural connections and panel lifting.

Likewise, the floor panels have threaded inserts cast at its four corners to allow for connection plates joining the floor panels to the wall panels to be bolted on. These inserts are also used to lift the floor panels for placement on the corbels. Once the floor panels are placed onto the corbels, a steel angle connection plate is inserted at the intersection of the floor and wall panel. Bolts through this connection plate connect wall panels to wall panels, floor panels to floor panels, and wall panels to floor panels. To create a flush interior finish, the connection plate is sunken into both the wall and floor panels. A simple cover can be snapped in place to hide the bolted connection.

Within the EPS foam insulation of floor and wall panels, electrical conduit is embedded to allow for the electrical, telecommunication, and data wiring. Openings in the panels can be carved out for light switches, electric outlets, phone and data panels, and ceiling mounted lights or fans. Where floor panels meet wall panels, openings are provided so that wiring can be run from the wall and through the floor to support floor outlets or ceiling mounted lights or fans.

The assembly process is relatively straightforward and will not require an extensive amount of skilled labor. First, the foundation for the building will be laid on-site using conventional construction methods. Depending on site conditions, it may be a slab-on-grade concrete foundation or a spread footing foundation. Once the foundation has cured, the wall panels for the ground and first floors of the townhouse will be lifted into position onto the foundation and supported upright by temporary shoring. When the wall panels are positioned and attached to the foundation, the corbels will be bolted in place. The corbels will also connect the various wall panels to each other. Next, the floor panels for the first floor will be lifted into position on top of the corbels and workers will bolt the connection plates into place. Shoring can be removed once the floor panels are bolted in place. This simple process is repeated for the wall panels and floor panels on the upper levels. Once the structural panels are all positioned and connected, interior partitions, window walls, shading devices, stairs and other building elements will be added. The entire assembly process can be completed in a short amount of time, saving money associated with on-site labor and allowing the building's interior to be immediately covered and protected.

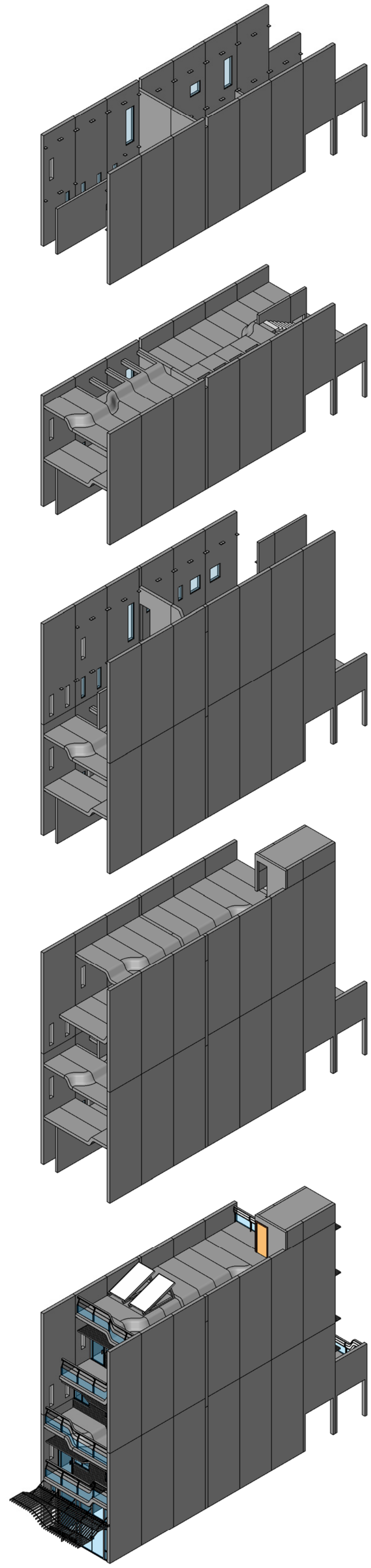


Figure 5.14. Construction Sequence Diagram

5.9. Design: Program, Plan, and Organization

Having established how the townhouse may fit into urban Honolulu sites and how the prefabricated panelized system will work, a specific townhouse prototype unit design solution can now be proposed. As specified earlier, the general organization of each mixed-use townhouse unit is a three-story 3 bedroom 2.5 bathroom residential that sits on top of a one-story leasable retail floor. In order to satisfy the various site configurations, each unit must be able to share two walls with adjacent units. The massing thus takes on a thin but deep “shotgun” layout, where only the front and back facades are always exposed. Spaces will have to be arranged in a linear pattern with circulation typically pushed to one side. The building is designed to be oriented along the north-south axis. Based on the site configurations and massing studies, the unit envelope will be approximately 18 feet wide by 60 feet deep by 50 feet tall. This prototype illustrates what a minimum configuration of the prefabricated SCIP panel system might look like in a mixed-use urban townhouse application.

The program for the interior spaces of the townhouse unit is typical of a 3 bedroom home. About one quarter of the interior building area is leasable retail, while the rest is residential. Exterior spaces are an important part of the design, and almost all rooms have access to private lanais. The rooftop of the townhouse is accessible, providing an additional outdoor space for the occupants to enjoy. Both the retail and residential entries are located at the front of the building, accessible from the sidewalk. Residential parking is pushed to the back, as the shotgun layout limits the amount of space for the retail storefront. The breakdown of the design program and areas is presented in the table below.

Table 5.2. Design Program for Oahu Townhouse Prototype Unit

Design Program			
Interior Spaces		**Exterior Spaces**	
Leasable Retail Space	850 sqft.	Residential Parking	250 sqft.
Living Room	300 sqft.	Living Room Lanai	50 sqft.
Dining Room	150 sqft.	Dining Room Lanai	125 sqft.
Kitchen	200 sqft.		
Half Bathroom	25 sqft.		
Utility / Laundry Room	50 sqft.		
Bedroom 1	150 sqft.	Bedroom Lanai	100 sqft.
Bedroom 2	150 sqft.	Bedroom Lanai	100 sqft.
Bathroom	75 sqft.		
Office / Study	125 sqft.		
Master Bedroom	200 sqft.	Master Bedroom Lanai	125 sqft.
Master Bathroom	75 sqft.		
Circulation	700 sqft.	Rooftop Terrace	150 sqft.
Total Interior Area	**3050 sqft.**	**Total Exterior Area**	**900 sqft.**

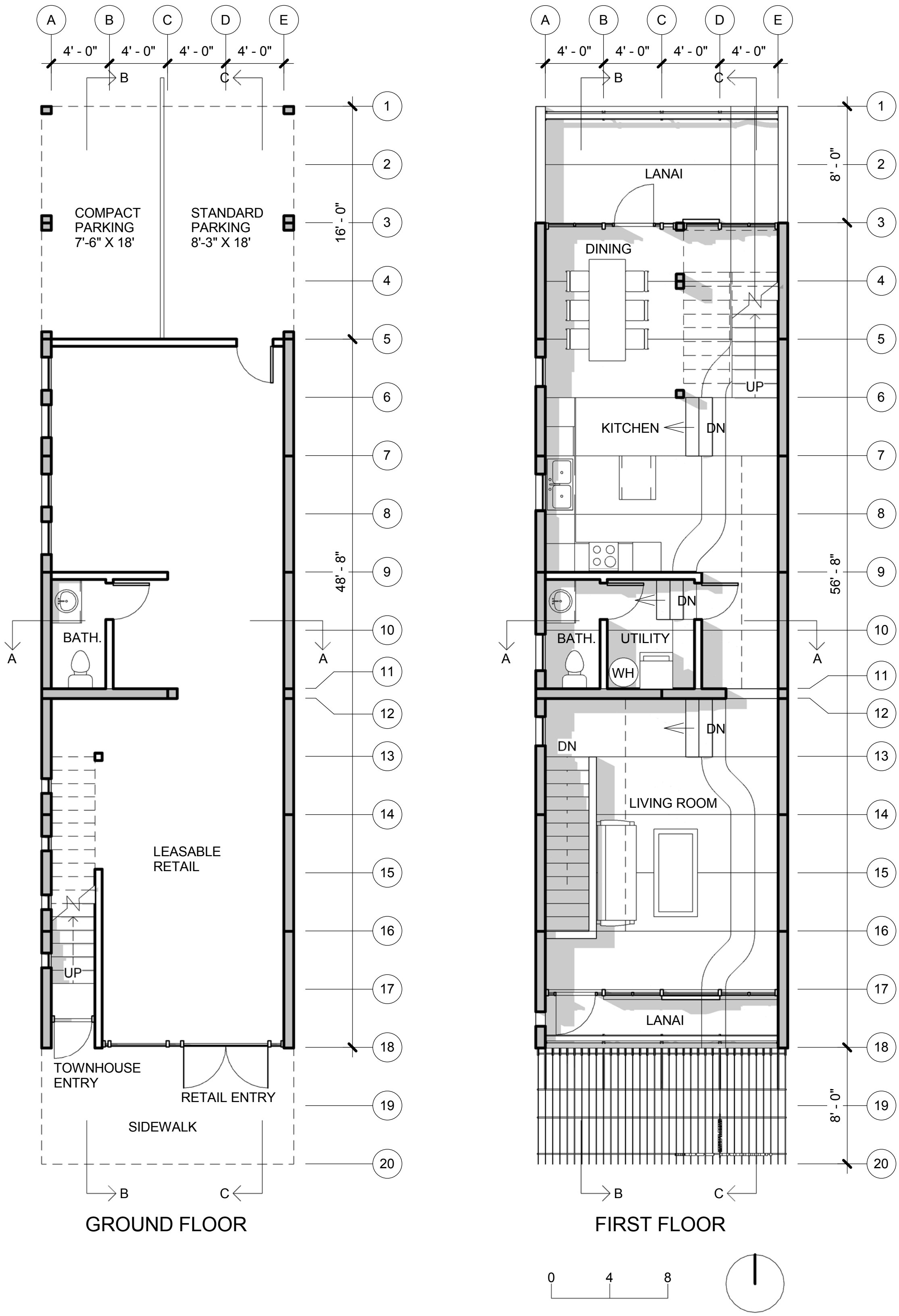


Figure 5.15. Ground and First Floor Plans

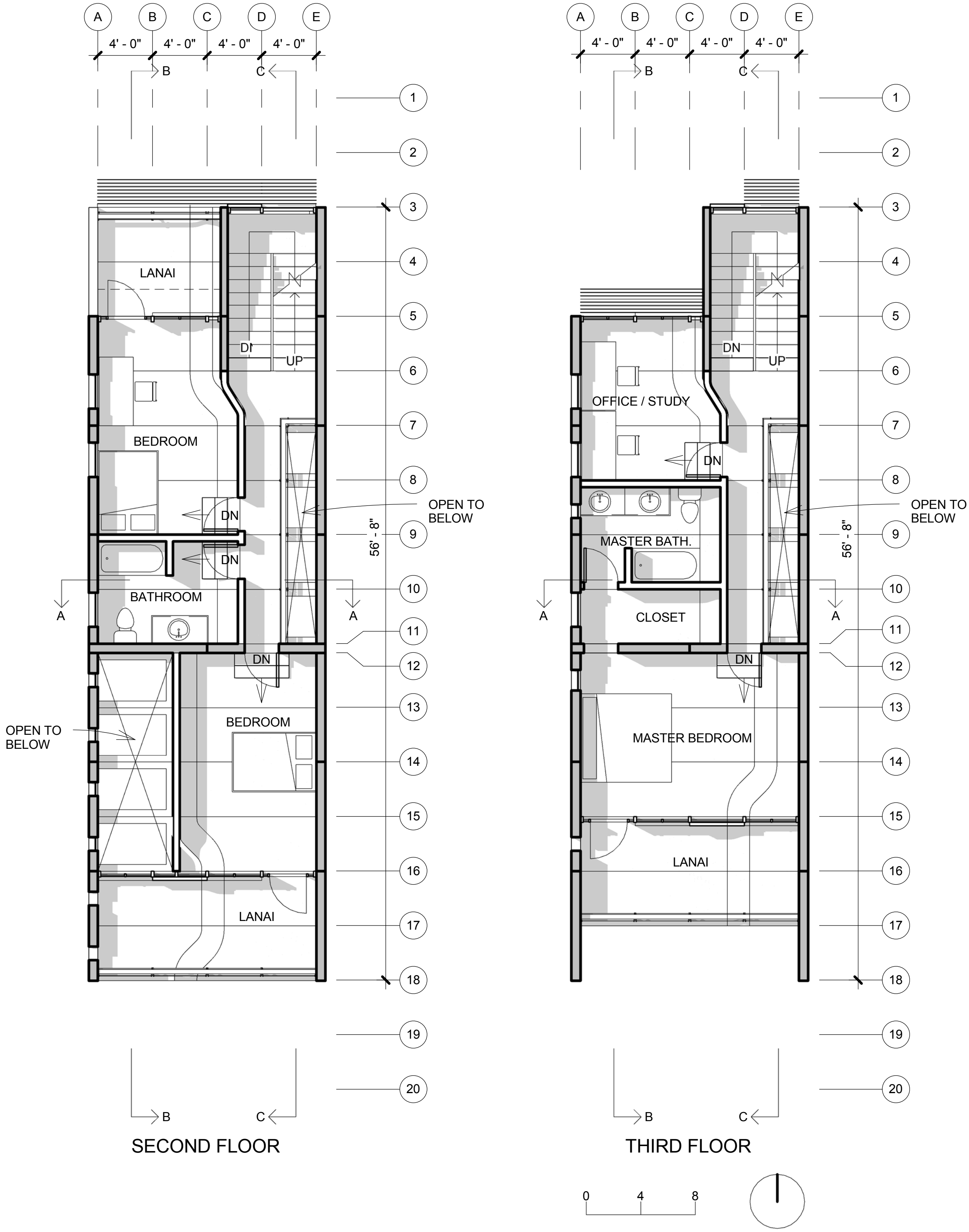


Figure 5.16. Second and Third Floor Plans

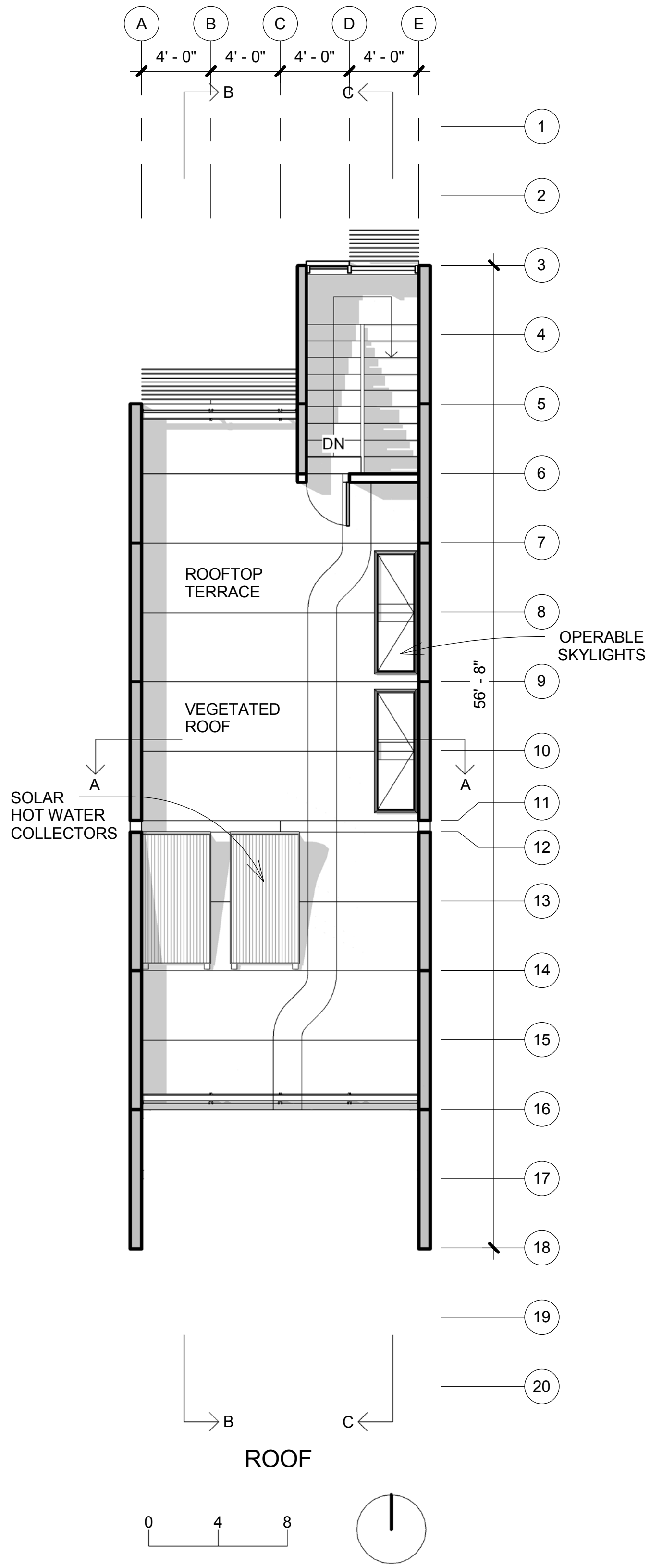


Figure 5.17. Roof Plan

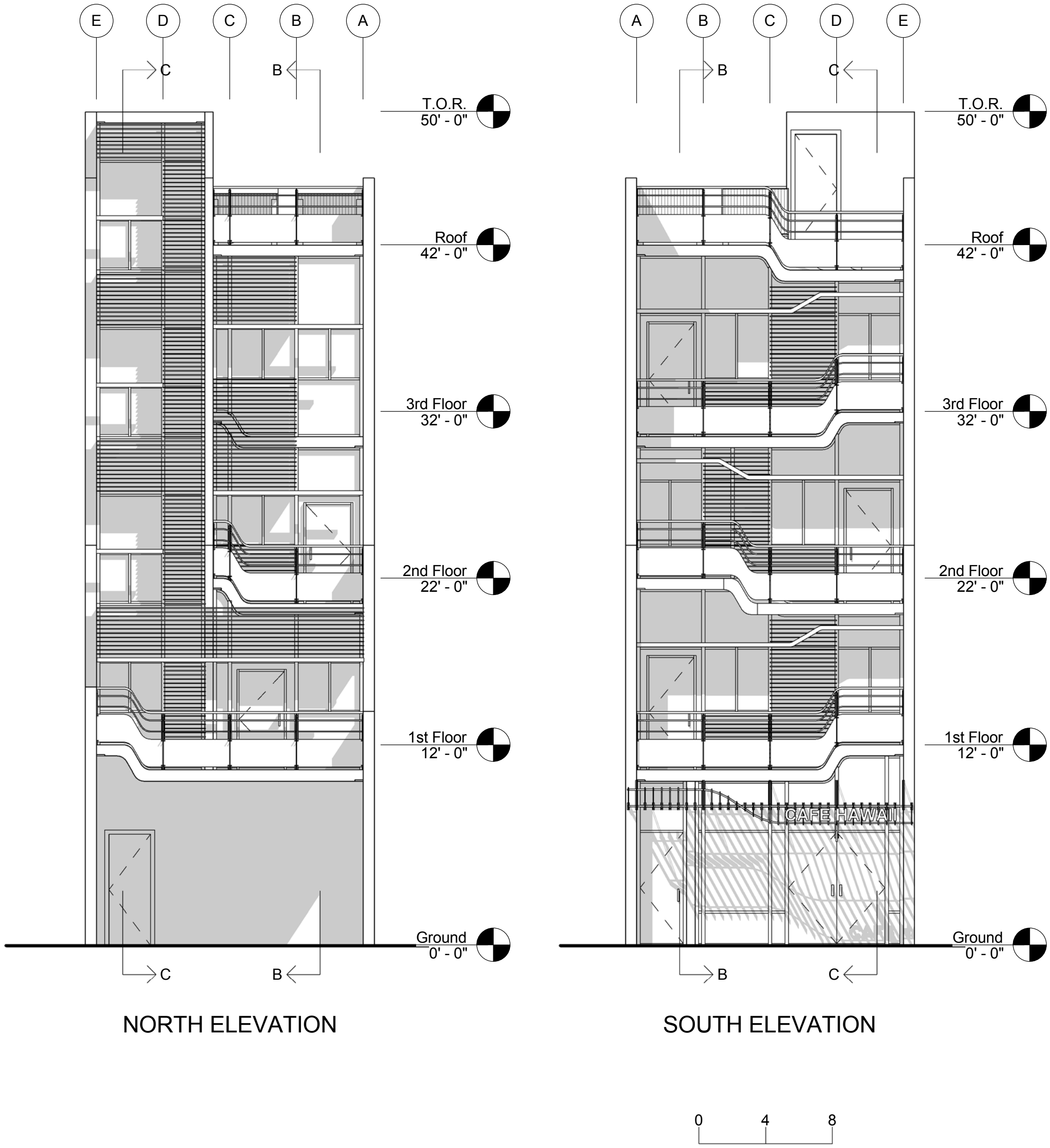
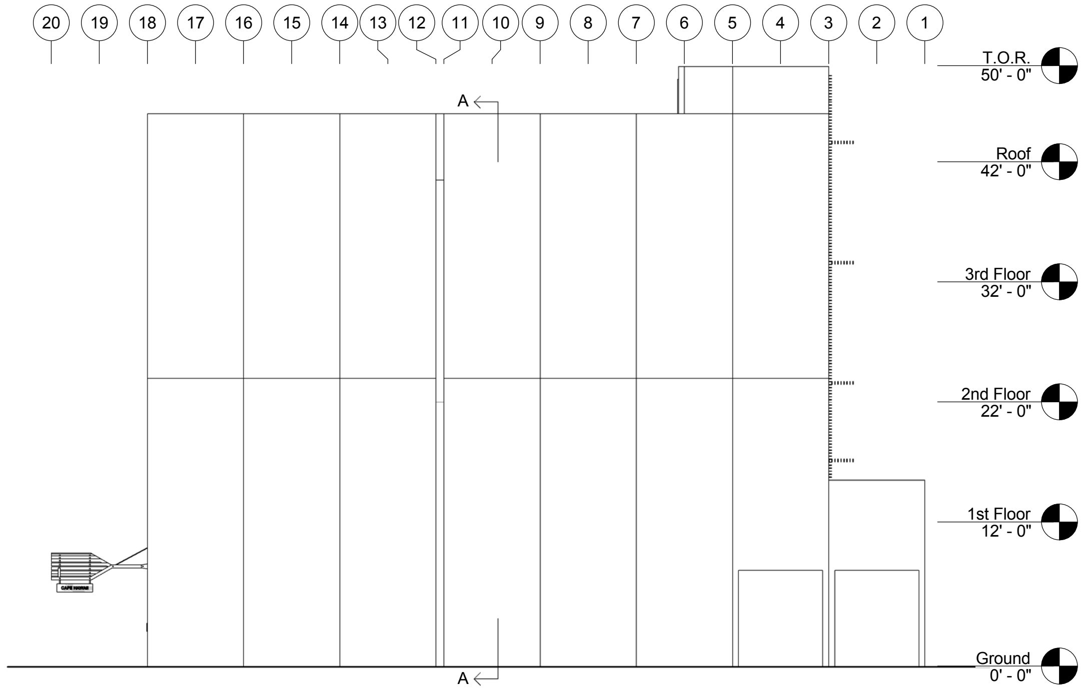
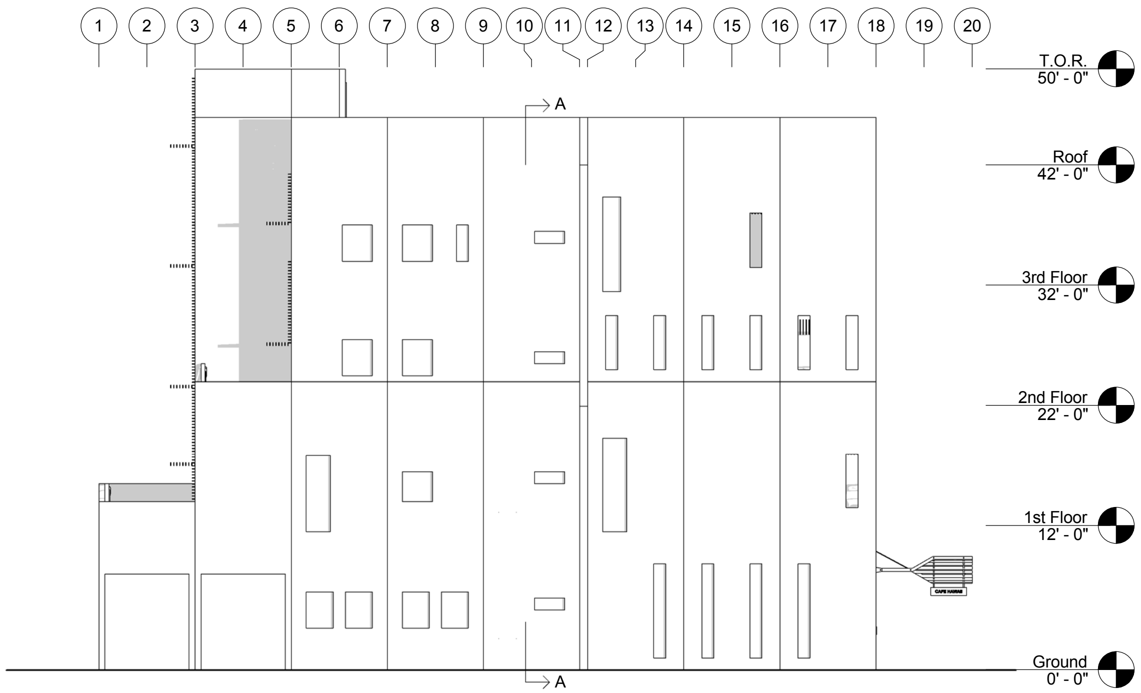


Figure 5.18. North and South Elevations



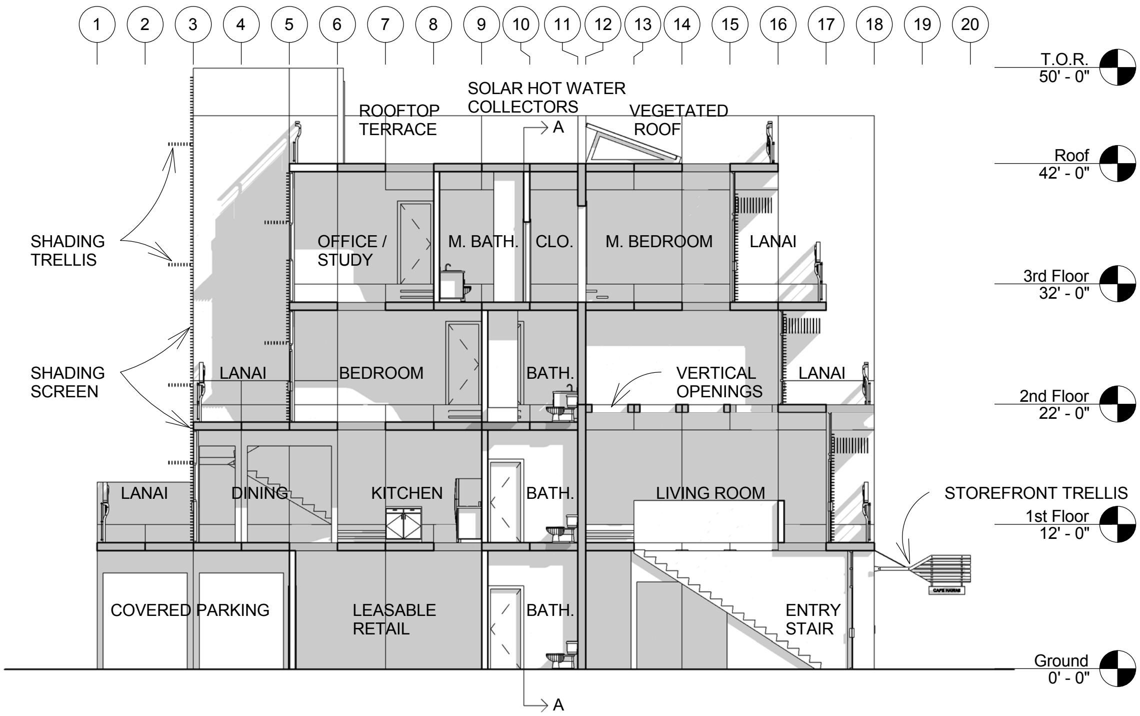
EAST ELEVATION



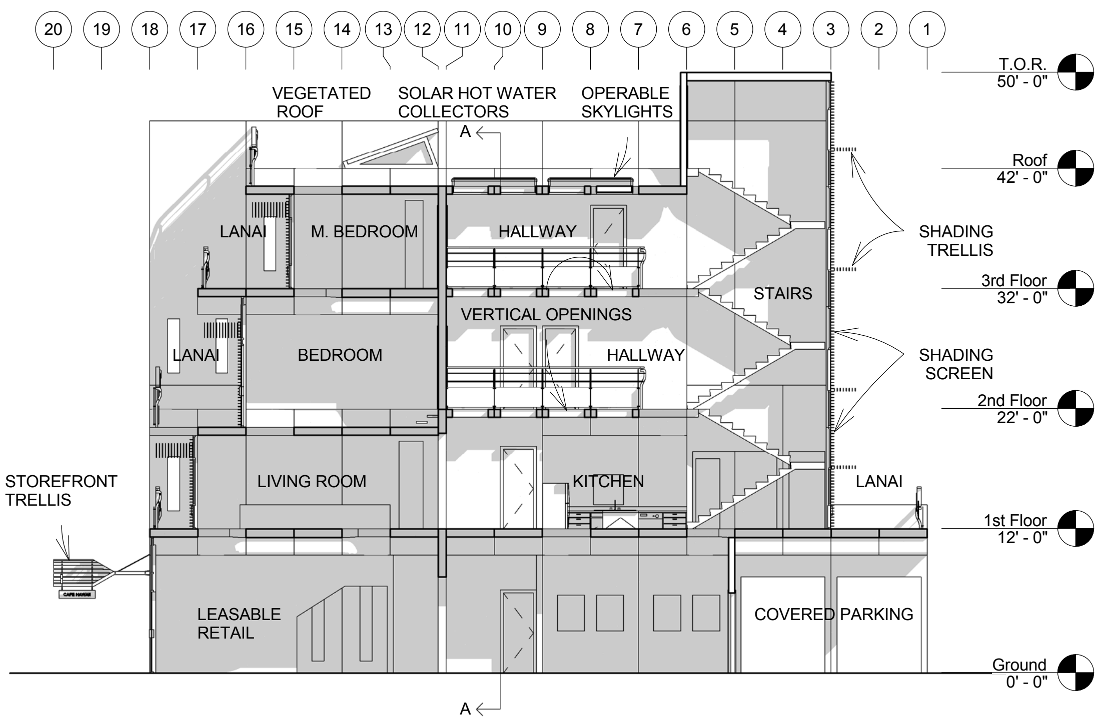
WEST ELEVATION

0 4 8

Figure 5.19. East and West Elevations



LONGITUDINAL SECTION B-B



LONGITUDINAL SECTION C-C

0 4 8

Figure 5.20. Longitudinal Sections

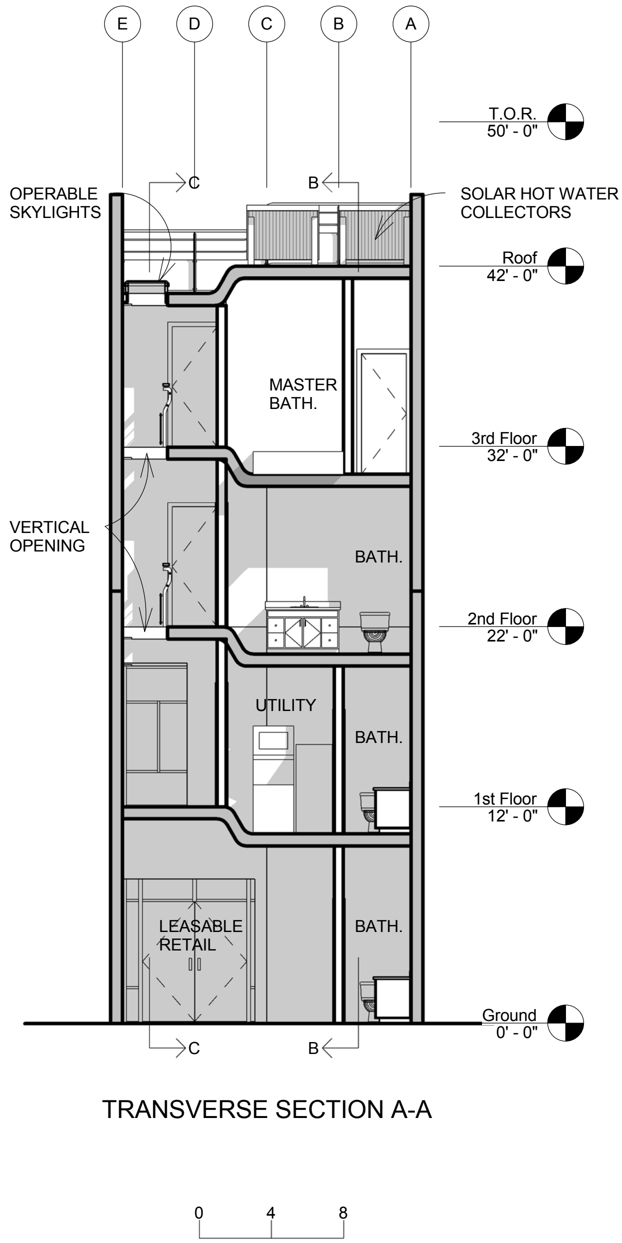


Figure 5.21. Transverse Section

At the ground floor level, a large storefront interfaces with the sidewalk and street. A custom designed wooden trellis hangs overhead to provide shading for the storefront. The elements of the trellis are designed from the same parametric model that the curved floor panels are based on. They can be precisely cut using a CNC laser cutter for assembly. The leasable retail space is an open space that can be designed according to the needs of the retailer. If two townhouses are located side by side, the buildings would be mirrored so that the party wall can be opened up at the ground level to create a retail space that is double in size. In the center of the building is a continuous concrete shear wall that runs up the entire building. This wall will also serve as the primary plumbing and HVAC wall using metal furring strips and drywall coverings attached to the shear wall to hide the vents, pipes, and ducts running vertically through the building. A bathroom and small storage area is located at this shear / utility wall. The bathroom spaces in the townhouse can conceivably be prefabricated modular units that simply plug into the utility wall. At the back of the retail space, an emergency exit door leads to the covered area where parking for the residents is located. If the west facing wall of the building is not a party wall, openings will be punched into the wall panels to support windows that allow natural lighting into the space. Although the floor of the retail space is flat with no elevation changes, the ceiling will reflect the elevation changes of the first floor of the townhouse, creating a flowing curving ceiling element that runs the length of the retail space.

At the western end of the ground floor façade, the townhouse entry is located. The entry is stepped back to offer more privacy and to differentiate it from the retail entry. The townhouse entry leads to a set of stairs that goes up to the first floor of the house. This staircase is located directly below a large double-height space that creates an entry experience that is both compressed due to the three foot width of the staircase but filled with light and space due to the height and glazing of the areas directly above. The staircase leads to the living room, which has a small 4 foot lanai in the front. Elevation changes in the floor plan of the first floor occur at the eastern end of the house. In the living room, this elevation change serves to lower the floor to create a higher ceiling and create raised spaces along the east wall for additional seating or the placement of a television, electronics, or display items. For the rest of the first floor, the raised space acts as the hallway space, with lower spaces defined off of the circulation path. Above this hallway are vertical openings that rise all the way through the house to operable skylights at the roof. This feature brings lighting down from above and also helps exhaust hot air from all floors out the top of the building. At the center of the building where the shear / utility wall is located there is a bathroom and a utility space. The utility space is used for laundry and also holds the water heater, main electrical panel, and other equipment. Again, both the utility and bathroom space can be prefabricated and pre-engineered modules that plug into the utility wall. Moving past the central bathroom and utility space, the house opens up to the kitchen and dining spaces. The dining space is along the north window wall, which opens up to a large lanai that can be used for outdoor dining. A staircase which provides access to the upper levels and the rooftop terrace is located at the northeast corner of the townhouse.

The second floor of the townhouse contains two bedrooms and a shared bathroom in between the rooms. As in the first floor, circulation is located on a raised floor elevation on the eastern side of the house. Both bedrooms step down into lowered spaces to create a space with a higher ceiling and to help define the rooms as distinct spaces off of the hallway. Both rooms have large private lanais that create extended living areas.

Part of the window wall on the south façade acts as a large clerestory window for the double height space below, bringing light down to the living room and entry staircase. The bathroom between the two bedrooms is a full bathroom is located along the shear / utility wall.

The master bedroom, master bathroom, and office / study are located on the third floor. The master bedroom has its own lanai to the south and it is stepped back from the front of the building. It has its own walk-in closet and bathroom. The raised floor portion of the master bedroom serves as display or seating areas while the lowered floor combined with a high ceiling above creates an expansive floor to ceiling height for the room. The flexible office / study space is slightly smaller than one of the bedrooms in the house and can be adapted to the needs of the resident.

The flat roof of the townhouse is accessible through the main staircase and functions as a rooftop terrace space for the residents. Much of the roof will be covered with natural vegetation to create a green roof that reduces heat island effect, provides additional rooftop insulation, and reduces storm water runoff. This space takes advantage of Hawaii's year-round pleasant climate to provide a private green open space for the occupants. The roof of the townhouse will also support solar hot water collectors and allow access to the operable skylights above the hallway circulation spaces along the eastern wall. Optional photovoltaic panels may be installed on the roof and mounted on a raised structure that creates an integrated shading device for the terrace.

Figure 5.22. Perspective Rendering of South Façade

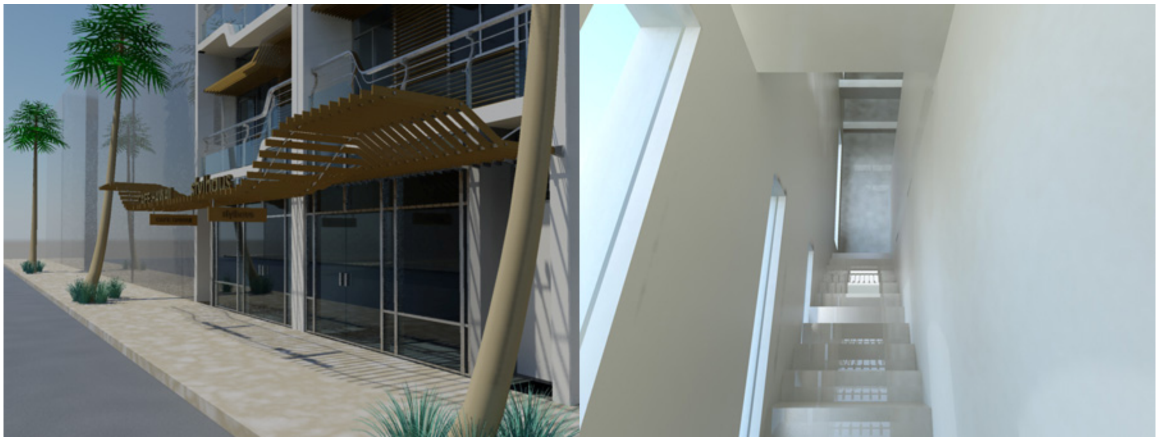


Figure 5.23. Perspective Rendering of Storefront Façade (left) and Residential Entry Staircase (right)

Figure 5.24. Perspective Rendering of Living Room

Figure 5.25. Perspective Rendering of Living Room (left) and Dining Room Lanai (right)

Figure 5.26. Perspective Rendering of Dining Room and Staircase

Figure 5.27. Perspective Rendering of Bedroom (left) and Master Bedroom (right)

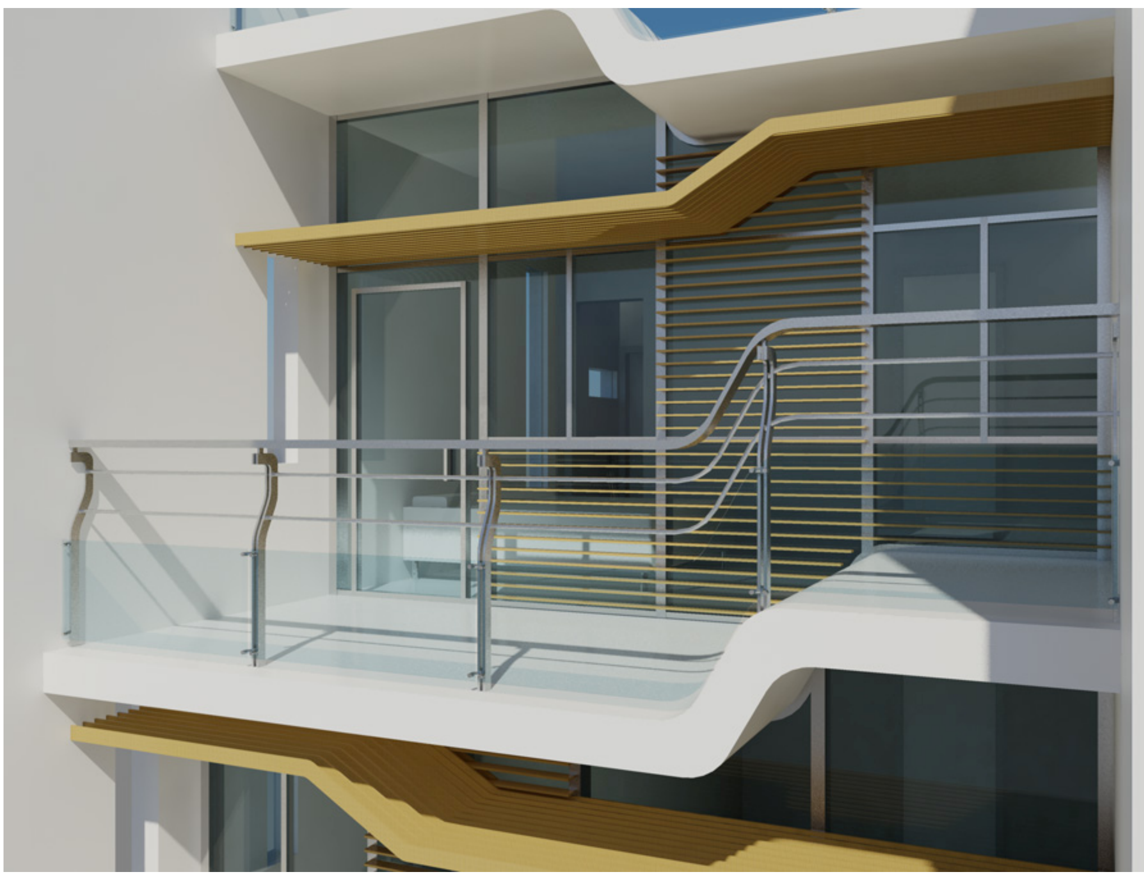


Figure 5.28. Perspective Rendering of Master Bedroom Lanai

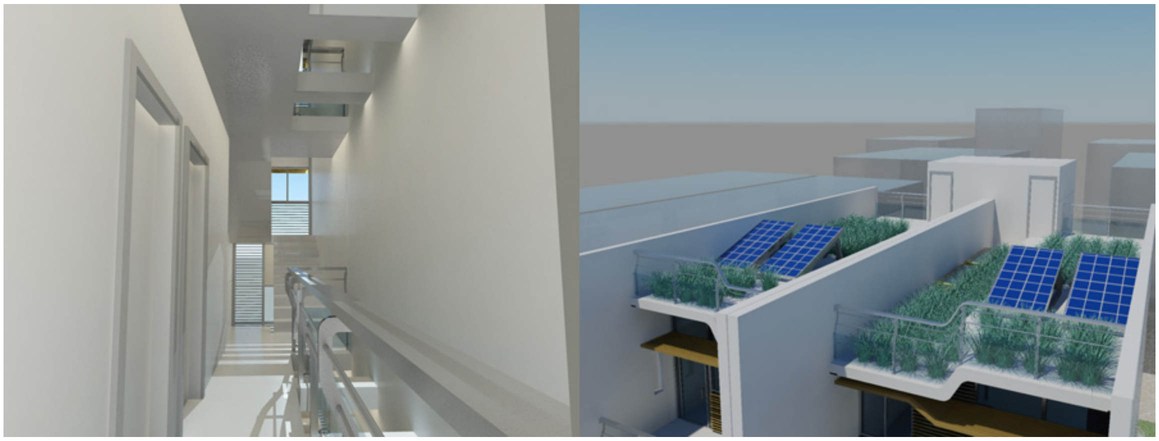


Figure 5.29. Perspective Rendering of Hallway (left) and Rooftop (right)

Figure 5.30. Perspective Rendering of North Façade

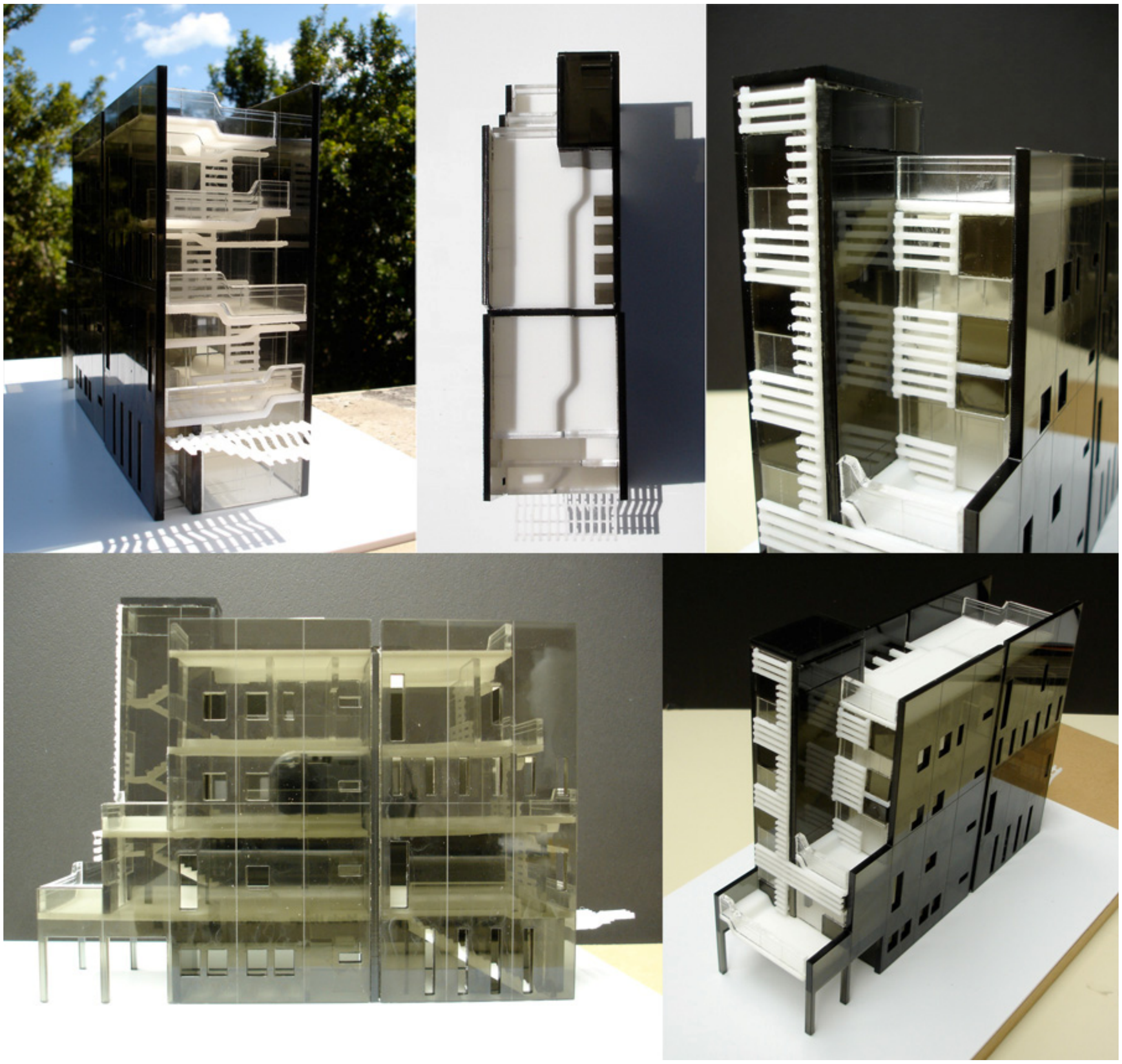
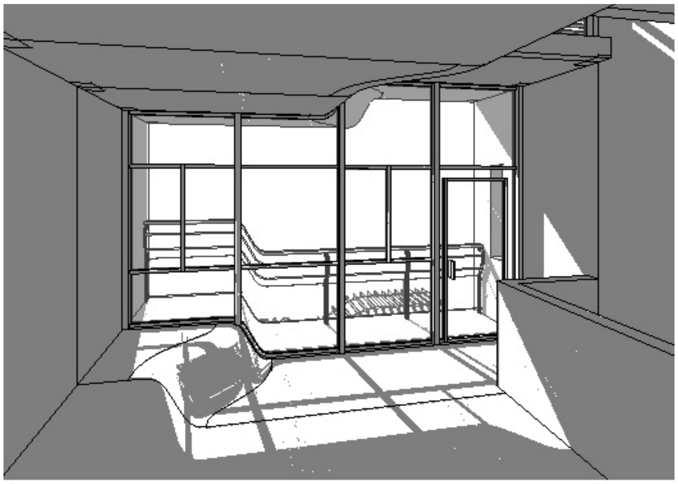


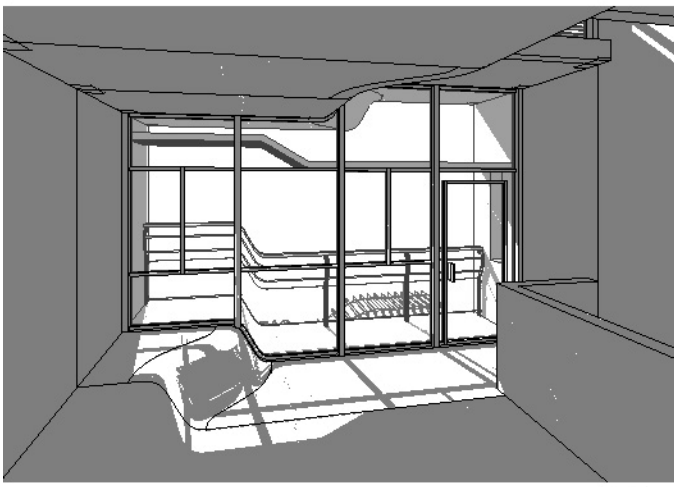
Figure 5.31. Photographs of Townhouse Scale Model

5.10. Design: Quality and Sustainability

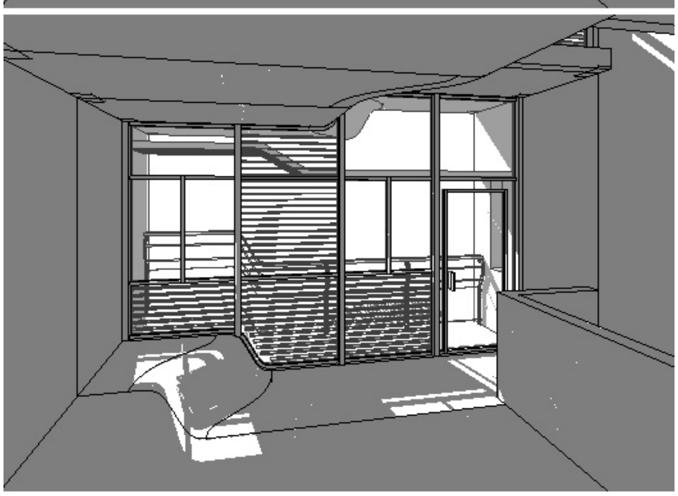
Utilizing primarily passive sustainable strategies, the townhouse prototype is designed to perform as a high-quality, energy-efficient residence for Honolulu's climate. The LEED for Homes building rating system has been used as a general guideline for the development of the townhouse. At the north and south façades, the building envelope is designed to maximize natural daylighting but minimize heat gain from direct sunlight entering the house. A variety of architectural elements are employed to accomplish this. The south walls are specified as floor to ceiling window walls in order to bring as much light in as possible. However, to block out direct sunlight, three distinct strategies are employed. At the 10 foot high typical window wall, the four foot overhang from the floor above blocks summer and winter sunlight from hitting the top third of the wall. For the second third of the wall, which includes operable windows, three foot deep shading devices are employed directly above which double as light shelves that reflect light deeper into the interior spaces. The shape and form of these shading devices are designed from the same parametric model the curved floors are based on. Again, almost no direct sunlight is able to hit the window and enter and heat the interior space. The bottom third of the window wall is protected by a bamboo louvered screen. The screen elements are three inches deep and spaced three inches apart. They provide some privacy inside the rooms while still allowing plenty of indirect daylight to enter.



Shade is provided for the top third of the window wall by a 4 foot overhang of the floor above



Shade is provided for the middle third of the window wall by a 3 foot shading device



Shade is provided for the bottom third of the window wall by a shading screen

Figure 5.32. Shading Studies for Living Room South Façade

The north window walls are treated similarly with shading devices and screens. Because there are no floor overhangs on this façade, solid insulated façade panels are also used to prevent sunlight from entering the building. Because the sun angles on the north side are not as low as on the south side, the shading devices do not need to extend out as far. However, if the orientation were to be reversed with the front facing the north and the back facing the south, the south side shading devices can easily be extended.

In the case that one of the east or west walls is not a party wall, it is possible to punch openings in the wall panels for the placement of windows. These windows will provide additional daylight and ventilation to various rooms. The window is set deeper into the wall for some protection from the sun and if necessary, screens can be placed over the window to minimize exposure to sunlight. The drawings of the prototype townhouse illustrate how these punched openings can be placed along the west façade.

To promote natural ventilation throughout the building, operable windows and doors are located on both the north and south window walls. Trade winds coming from the northeast will thus be able to pass through the openings on the north and out the openings on the south. Every room has windows so it will be possible for occupants to adjust their ventilation needs as necessary. At the hallway along the eastern wall of the townhouse, openings penetrate each floor above to the roof level, where operable skylights are placed. These skylights allow light to enter from above and provide lighting at each floor. They can also be opened to allow hot air rising through the building to be flushed out. If additional mechanical air conditioning is desired, a central system or window based units may be installed.

The vegetated green roof provides many sustainable benefits for the townhouse. Native species that require little maintenance and no additional irrigation will be placed on top of the roof. These plants will provide additional rooftop insulation, which is very important thermal barrier. When it rains, water will be absorbed by the plants, reducing the amount of storm water runoff from the roof and also filtering out pollutants in the rainwater. Soft vegetated roof surfaces will reduce heat island effect, since materials that would normally absorb solar radiation and re-emit heat are covered or replaced by plantings. Solar hot water collectors will be placed on the roof to eliminate the need for electric or gas based water heating. Optionally, a photovoltaic system can be installed on the roof to provide some renewable energy to the townhouse.

As mentioned in the descriptions of the wall and floor panel construction, recycled content will be used in almost all of the building components, including the EPS foam, concrete, and steel. Bamboo is a rapidly renewable material and will used for most of the screening and shading devices. Overall, the composite panels combined with shading devices will provide good insulation values that increase the thermal performance of the building envelope.

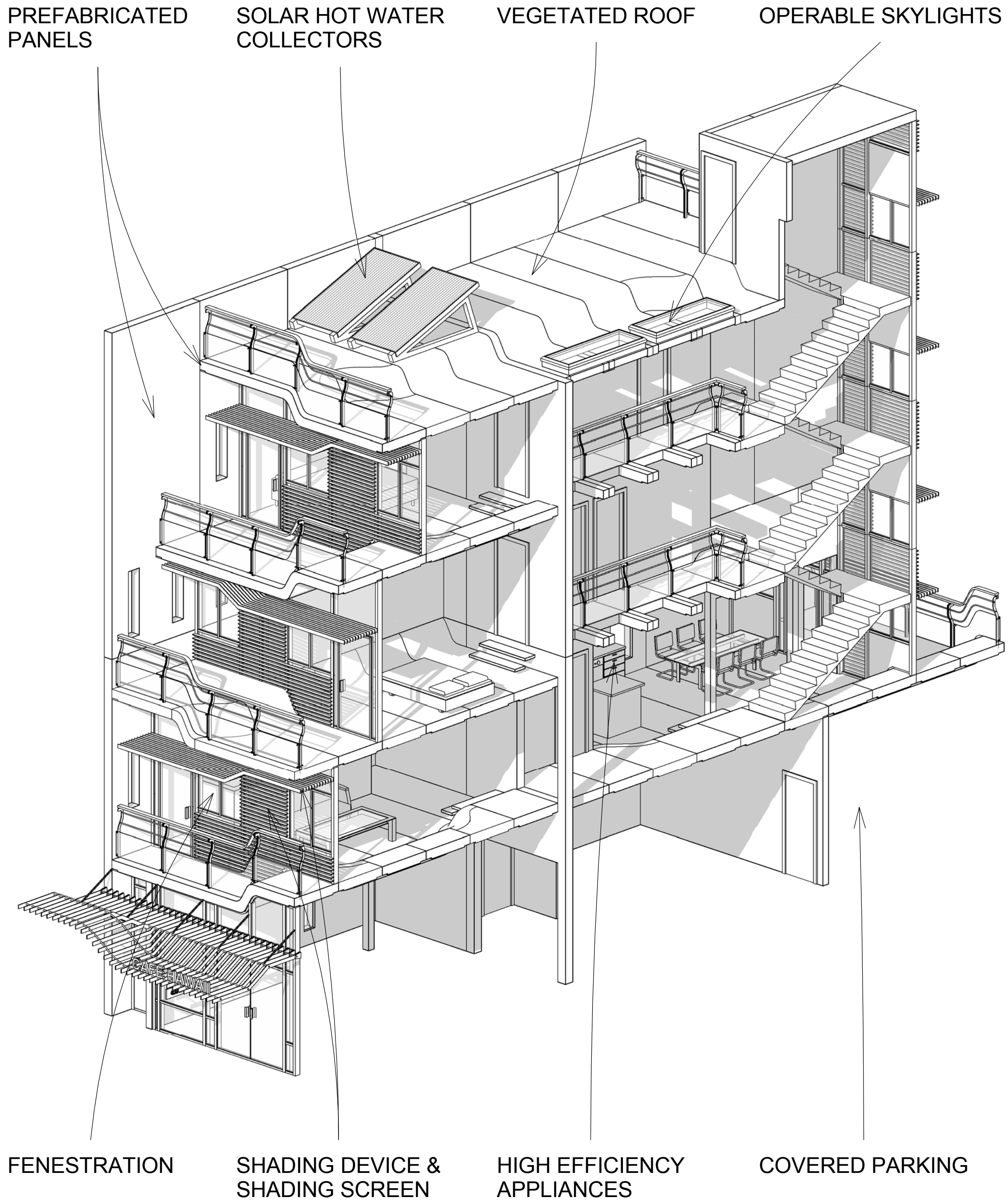


Figure 5.33. Diagram of Sustainable Features

5.11. *Design: Alternative Configurations*

The ability to fabricate parametric variations of the floor and wall panels opens up the opportunity to design interesting alternative configurations. The townhouse prototype is just one example configuration that relates to an urban setting with hypothetical site constraints and massing goals. The ability to develop other building configurations is important because most sites will have unique features and restrictions. The proposed kit-of-parts panel system allows for more creative liberty during the design stage. The panel size and panel features can be adjusted to create several unique parts that can be used to generate a variety of building shapes and forms.

To display the flexibility of the SCIP panel system, two alternative configurations will be conceptually developed, using the constraints of the parametrically variable wall and floor panels. The first alternative configuration is another urban housing prototype that is designed for a slightly larger site with a lower height limit. The second alternative configuration will explore the design of a larger scale high-rise apartment building.

The first alternative housing configuration assumes a slightly larger site and the building stands on its own with no shared walls with other units. It is in essence a single family home developed for a mixed-use urban neighborhood. Instead of a solely linear arrangement, an L-shaped layout has been designed, with the space within the L-shape serving as a carport. Like the original townhouse configuration, the ground floor level contains a leasable retail component, with the residential entry off to the side and stepped back from the front façade. However, the residential component above is only two stories and the main living spaces are located on the top floor instead of the first floor. Entering the residence, a straight run of stairs leads all the way to the top floor where the living room, dining room, and kitchen are located. A large lanai serves as an outdoor living room space and outdoor stairs on the lanai lead to the rooftop terrace and vegetated roof. Bedrooms are all located on the first floor and each room has its own private lanai. Many of the sustainable features implemented in the townhouse prototype will also be used in this housing configuration.

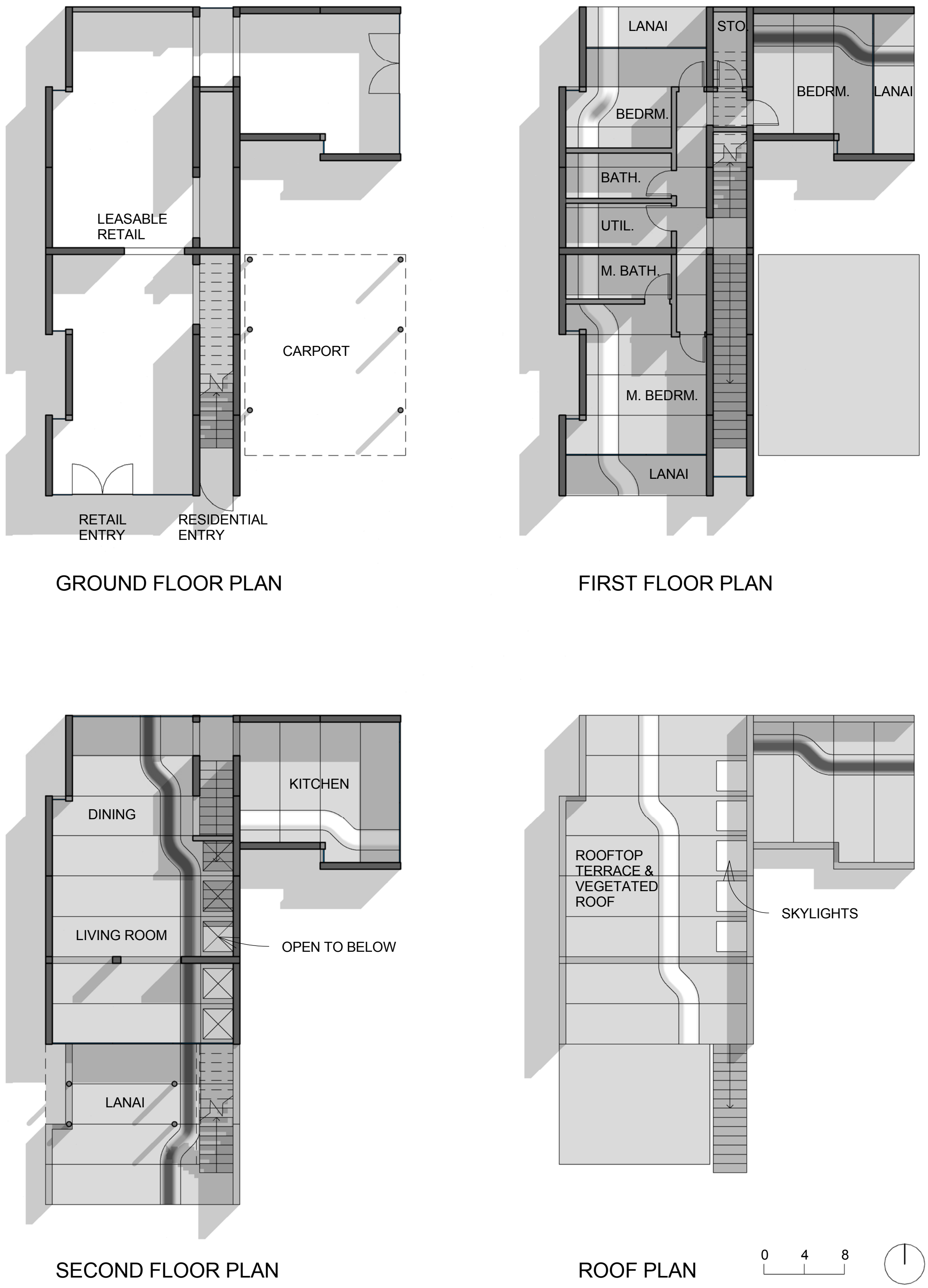
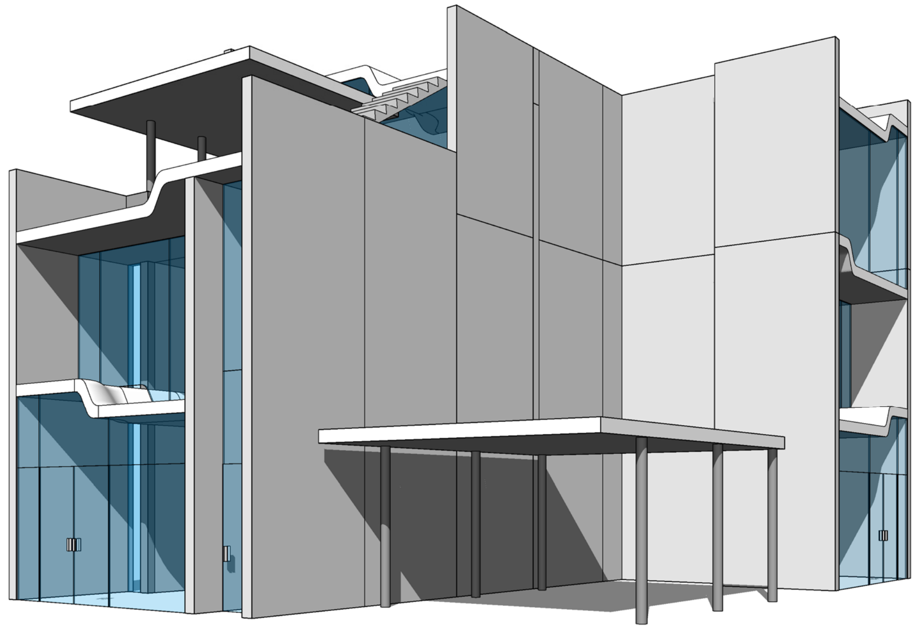
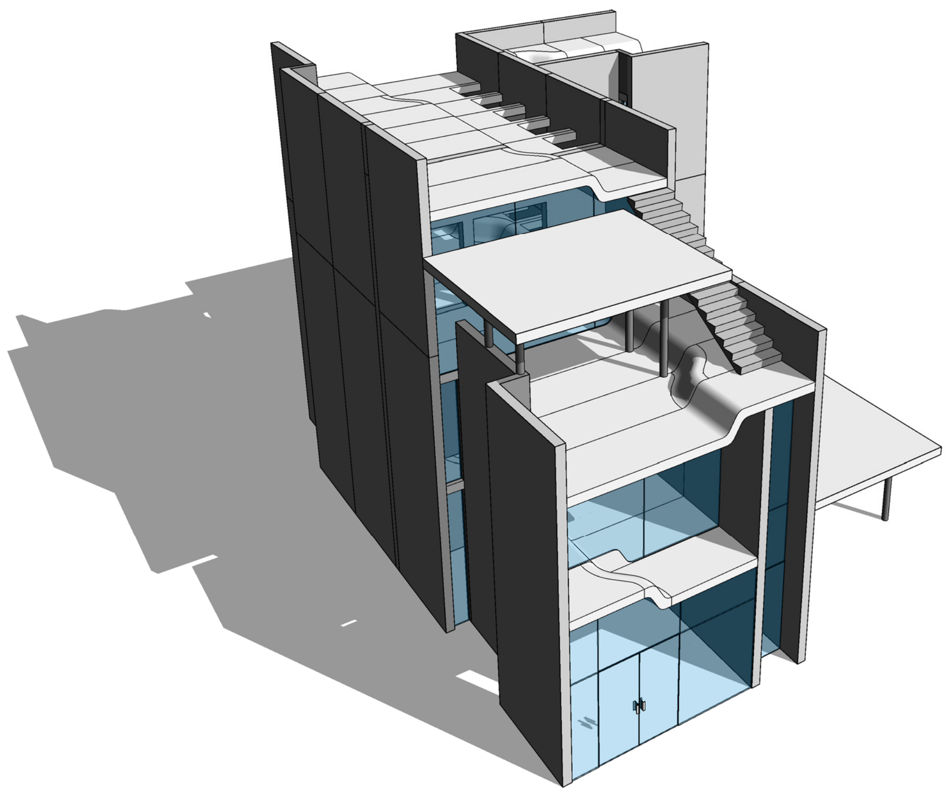


Figure 5.34. Floor Plans for Alternative Residential Configuration



EXTERIOR PERSPECTIVE SOUTHEAST

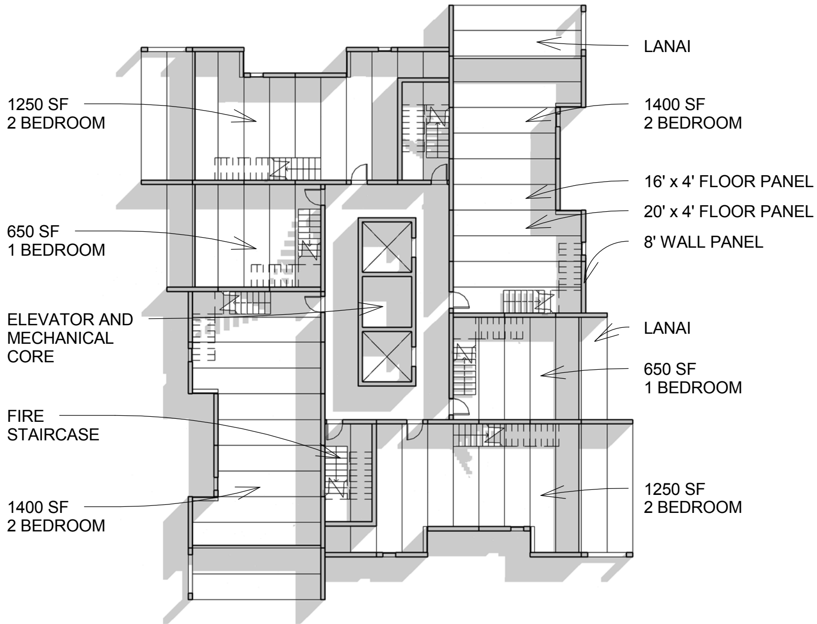


EXTERIOR PERSPECTIVE SOUTHWEST

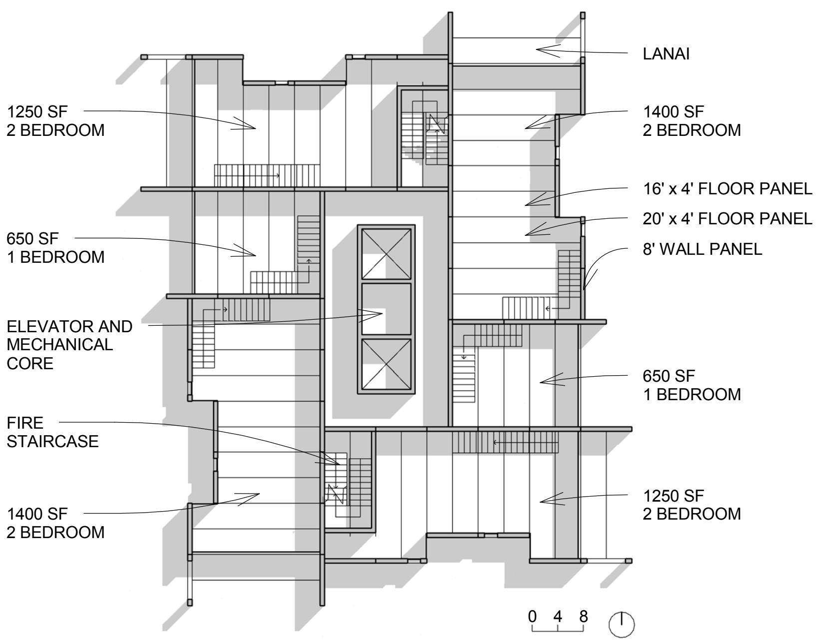
Figure 5.35. Exterior Perspective Views of Alternative Residential Configuration

Without the restrictions posed by shared party walls, there is the opportunity to introduce more variation along the major lengths of wall panels. Certain wall panels are set further in to create tectonic shifts that introduce pockets of light into the spaces. Where this happens, a shorter floor panel is used, which would be easy to fabricate through parametric variation of the length dimension. Elevation changes in the floor panels are used as they were in the townhouse prototype, creating seating and display areas in rooms while altering the floor to ceiling heights of rooms to create unique indoor environments.

The high-rise apartment configuration offers an exciting opportunity to use the panelized system for larger scale applications. In this configuration, an 18 story residential tower designed from the wall and floor panels sits on top of a three-story retail platform. Each of the units is a two-story loft. There are four 2 bedroom units and two 1 bedroom units for every two floors of the apartment, creating a total of 54 units. The units surround an elevator and mechanical core. A covered public garden terrace is placed at the top of the building for residents to enjoy. Above the garden terrace, equipment for central air conditioning and rainwater harvesting is located.



LOWER LEVEL PLAN



UPPER LEVEL PLAN

Figure 5.36. Typical Unit Plans for High-Rise Configuration

EXTERIOR PERSPECTIVE WEST

EXTERIOR PERSPECTIVE SOUTH

Figure 5.37. Exterior Perspective Views for High-Rise Configuration

Whereas a typical high-rise might look identical from floor to floor, the ability to easily vary floor and wall panels can create a more interesting and dynamic exterior aesthetic. In this design there are three different 2 bedroom unit types, each with a different floor panel expression at their lanais and a different punched opening configuration along their exposed wall panels. It is conceivable that owners would be able to select a desired unit configuration in advance, introducing an element of personalization to a normally repetitive building type.

Structurally, panels at the base can be fabricated to be thicker and stronger in order to support all the panels above. Additional connections and structure would have to be designed and engineered for a larger scale application of this type. However, the majority of the fabrication and assembly processes would be able to take advantage of the prefabricated panel system.

The original townhouse prototype and these two alternative configurations display the value and flexibility of a prefabricated system developed with modern technologies and tools. A balance between cost, performance, innovation, standardization, variation, and customization can be shown to be within the reach of designers, builders, developers, and buyers through modern prefabrication technologies.

6. Conclusion

At the core of this investigation into architectural prefabrication technologies are two higher agendas. The first relates to the homebuyer in Honolulu, who wishes to purchase the highest quality home that his or her money can afford. In this regard, prefabrication has been shown to be an effective tool to design and build unique, sustainable, energy-efficient homes using cost-effective technology driven fabrication methods. Under this context, prefabrication is not a solution to the unaffordability of homes in Hawaii, but rather a method to improve the subjective and objective quality of homes without increasing the cost of construction. It offers the homebuyer an opportunity to purchase a home built from modern material assemblies and modern fabrication processes; a home that can also be customized and configured to meet their changing needs. Through prefabrication they can finally get more for less.

The second agenda speaks to the architect's role in the design and construction of housing. The architect sees the declining quality of homes in Honolulu and wants to offer alternative housing solutions that integrate well designed spaces with sustainable design principles. Where the cost of custom design and construction services previously priced them out of the general housing competition, modern prefabrication now allows them to design high-quality homes at lower cost using advanced standardized construction concepts. A thorough understanding of the tools and technologies available for prefabrication will allow architects to either compete against developers or provide design and fabrication management services to them.

For architects, the benefits of prefabrication go beyond being able to provide high-quality design at competitive prices and getting opportunities to design more residential projects. Modern prefabrication is providing a way for architects to reconnect to the craft of making, a skill that has been gradually passed over to the domain of contractors as the building industry has grown increasingly specialized. When architects must work closely with fabricators at the earliest design stages, they will naturally develop a greater understanding and appreciation of the opportunities and limitations of the physical building process. This design interaction will inform their future projects, giving them a more comprehensive vision of how their designs are built and put together. Architects that pursue prefabrication in their designs will inevitably have a deeper understanding of how their building really works.

Today, architects directly have the resources and tools to digitally design prefabricated building components that they directly can build or prototype themselves. Advanced software suites allow detailed construction to take place in the digital world where conflicts can be resolved ahead of time. CNC machinery further results in a seamless transition from the digital world to the real world. All of these technologies become faster and cheaper every year, opening them up to larger markets. Accessibility will allow more architects to experiment with these prefabrication technologies. With more experimentation, future innovations and discoveries in design and construction will be made. Prefabrication now has the opportunity to make significant changes in the industry through the grassroots-like efforts of architects who want to take on the challenge and embrace it as the primary way they will design and build.

The townhouse prototype proposed intends to inspire both homebuyers and architects to demand change in the current offerings of homes in Honolulu. On one hand, it promotes an alternative pattern of housing development for the future. On the other hand, it gives a specific example of how prefabrication can be used to produce a high-quality house.

The broader issues of development are the ones that can actually help provide a solution to the affordability problem. Land being limited and expensive in Honolulu, it makes sense to build in a denser pattern that focuses on creating vibrant pedestrian oriented communities that offer a rich mix of uses. Transportation and utility infrastructure are important considerations in the planning of these mixed-use mid-density urban neighborhoods. The three proposed site configuration and massing studies offer a look at how a townhouse might fit into the goals of a mixed-use development.

In the townhouse prototype, the details of a specific prefabricated system are designed and analyzed. A structural concrete insulated panel system is developed for a design concept that challenges uniform floor panel elevations. This concept introduces spatial innovation in urban residential architecture while the panel system utilizes digital prefabrication techniques. Parametric design allows over 60 unique panels to be developed based on three base geometries, meaning that at minimum, only three reusable concrete forms need to be created to fabricate every SCIP panel in the building. This concept of mass customization in turn results in a design flexibility that accommodates several alternative building configurations.

Hawaii is not the only place where housing quality is subpar or where a growing population and limited land is making denser development a logical move. The ideas and systems developed in this project can be applied to other areas in future studies. With its high insulation and structural efficiency, the SCIP system can be adapted to other climates with few adjustments. As shown with the alternative configurations, the building design can be easily reworked to accommodate different site conditions.

Further development of the SCIP engineering and fabrication process is warranted for the townhouse prototype to become viable. This would include linking up with fabricators to refine the design and to determine the setup and production costs involved in this type of panel production. Alternatively it might also be valuable to explore designs utilizing other materials and prefabricated structural systems, including ones that would not require the services of an outside fabricator and could be built entirely with CNC milling and cutting machines. Another future area of development lies in the internet marketing of the townhouse prototype and other configurations developed from the SCIP system. The technologies inherent in the prefabrication process lend themselves well to offering opportunities for a digital interface that allows homebuyers to extensively research and configure homes.

As long as there is a recognized problem in the way homes are designed, built, and sold in Hawaii, there will be a movement to find a solution. Changes are inevitable as the population continues to grow and the demand for quality housing increases. Being as accessible to architects as it is today, modern prefabrication has proved itself to be one of the most promising solutions. It is time for architects in Hawaii to take the lead in providing better housing and show what they can do when they take building fabrication and assembly into their own hands.

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9. Glossary

Apartment Mixed Use District (AMX)

The purpose of the apartment mixed use districts is to allow some commercial uses in apartment neighborhoods. The additional commercial uses shall be permitted under varying intensities and are intended to support the daily and weekly commercial service needs of the neighborhood, conserve transportation energy by lessening automobile dependency, create more diverse neighborhoods and optimize the use of both land and available urban services and facilities. Mixing may occur horizontally and vertically, but controls are established to maintain the character of these neighborhoods primarily as apartment neighborhoods.

Building Information Modeling (BIM)

A building information model is a digital representation of the building process to facilitate exchange and interoperability of information in digital format. The information is generated and managed throughout the design and construction process. Common BIM software in the architectural profession include Revit, ArchiCAD, and Microstation.

Business Mixed Use District (BMX)

The purpose of the business mixed use districts is to recognize that certain areas of the city have historically been mixtures of commercial and residential uses, occurring vertically and horizontally and to encourage the continuance and strengthening of this pattern. It is the intent to provide residences in very close proximity to employment and retail opportunities, provide innovative and stimulating living environments and reduce overall neighborhood energy consumption.

Computer-Aided Design Systems (CAD)

A digital interactive design and analysis environment for making digital geometric models of the object to be eventually produced. Common CAD software used for CAM include CATIA, SolidWorks, and Unigraphics.

Computer-Aided Manufacturing Software (CAM)

Computer-aided manufacturing software is used to specify how the digital design model is to be actually manufactured and creates a series of digital instructions for controlling specific machines. Typically CAM software will take a digital model created in a CAD system as input and output specific instructions for the machine which is to produce the object.

Computer Numerical Controlled Machines (CNC)

Computer numerically controlled machines translate digital instructions into actual machine operations that make the object. Machines include CNC milling machines, routers, lathes, drills, saws, laser cutters, water jets, electric discharge machines, welders, and more. These machines either fabricate the objects directly or create negative molds for casing or injection molding.

Digital Design and Manufacturing

Digital design and manufacturing is composed of three component systems that work to together. The components are a CAD system to generate the geometric models, CAM software to create digital instructions for the tooling of the models, and CNC machines to translate the instructions into actual machine operations.

Expandable Polystyrene (EPS)

Expandable polystyrene can be used as an insulating material in construction. Containing a blowing agent, it is produced by the polymerization of a styrene monomer in the presence of a peroxide as catalyst, causing the styrene molecules to form long chains. This allows it to be easily molded into low-density foam parts.

Fiber-Reinforced Concrete (FRC)

Concrete containing short discrete fibers that are uniformly distributed and randomly oriented in order to increase its structural integrity. Fibers types include steel fibers, glass fibers, synthetic fibers and natural fibers.

Leadership in Energy and Environmental (LEED)

LEED is a third party certification program and the nationally accepted benchmark for the design, construction and operation of high performance green buildings. The LEED Green Building Rating System encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria.

Manufactured / Mobile Homes

Manufactured homes are built with a permanent internal structural support system (a steel chassis) that allows them to be supported by wheels for transportation. They commonly are composed of one building module twelve to fourteen feet wide by seventy or more feet long (single-wide) or two building modules that allow the width to increase to twenty-four feet or more (double-wide). The construction and installation of manufactured homes is regulated by the U.S. Department of Housing and Urban Development (HUD).

Mass Customization

The ability for product modularization and mass production to be customizable without downtimes, setup times, and high-cost tooling changes. Production in mass customization is typically driven by actual orders rather than predicted demand, reducing the cost for storage of unsold items.

Mixed-Use Development

In mixed-use development, more than one type of use is allowed in a single building or a set of buildings. A building can be a combination of residential commercial, industrial, office, institutional, and other land uses.

Modular Homes

Modular homes are factory constructed and need enough internal strength and stability to be transported to their permanent site and lifted or craned into position. They are composed of one or more modules, each whose size is limited by state transportation laws. Once on site, modules may be stacked, placed side by side, or arranged in any other format specified by the design.

Panelized / Componentized Homes

In panelized homes, flat component assemblies such as wall panels, roof trusses, partitions, and floor assemblies are built in the factory and then shipped out to the site where they are assembled. Components like wall panels will often be nearly finished with windows, doors, wiring, and exterior siding. Panelized homes are generally easier and cheaper to ship as they can be compactly bundled and moved on fewer and smaller vehicles.

Parametric Design

Parametric design is a method of linking dimensions and variables to geometry in such a way that when the values change, the part changes as well. A parameter is a variable to which other variables are related, and these other variables can be obtained by means of parametric equations. Families of parts can be created which can be easily without having to redraw or redesign for each variation.

Pre-cut Homes

All the materials to build the house are pre-cut and then shipped out to the site where they are assembled. These pre-cut materials are the basic elements of the house and are not yet assembled into more detailed components and assemblies. Therefore a significant amount of on-site work is still required. Examples of pre-cut homes include catalog kit homes, log homes, and dome homes.

Prefabrication

In the building industry, prefabrication is the concept of producing building components in an efficient work environment with access to specialized skills and equipment in order to reduce cost and time expenditures on the site while enhancing quality and consistency.

Structural Concrete Insulated Panel (SCIP)

Structural concrete insulated panels are composed of a layer of rigid foam insulation sandwiched between two concrete wythes. Reinforcement is typically provided by embedding steel welded wire mesh into the concrete wythes. Additional shear support can also be provided through embedded trusses.

Structural Insulated Panels (SIP)

Panels are typically made by sandwiching a core of rigid foam plastic insulation between two structural skins of oriented strand board (OSB). The resulting composite panel acts as a structural I-beam or I-column, with the foam acting as the web and the OSB sheets as the flanges. SIPs are prefabricated, structurally efficient, provide excellent insulation, and can be cut to custom sizes. They can be used in floor, wall, and roof applications.

Townhouse

The physical form of two or more single-family attached homes with a ground floor entry. Ownership of the townhouse is similar to ownership of a single-family home, with a community association usually holding the title to any common property.

Transit Oriented Development (TOD)

A form of development that emphasizes smart, sustainable, and healthy growth and planning by providing a mixture of uses that provide denser, pedestrian and public transit oriented areas for living, working, and playing. TOD typically looks at an area about one quarter mile around a transit station and establishes minimum densities for commercial and residential zones, minimizes the amount of off-street surface parking around commercial buildings by moving parking underground and into structures, and plans a variety of housing densities, types, prices, and ownership patterns that are all within walking distance to the transit nodes.